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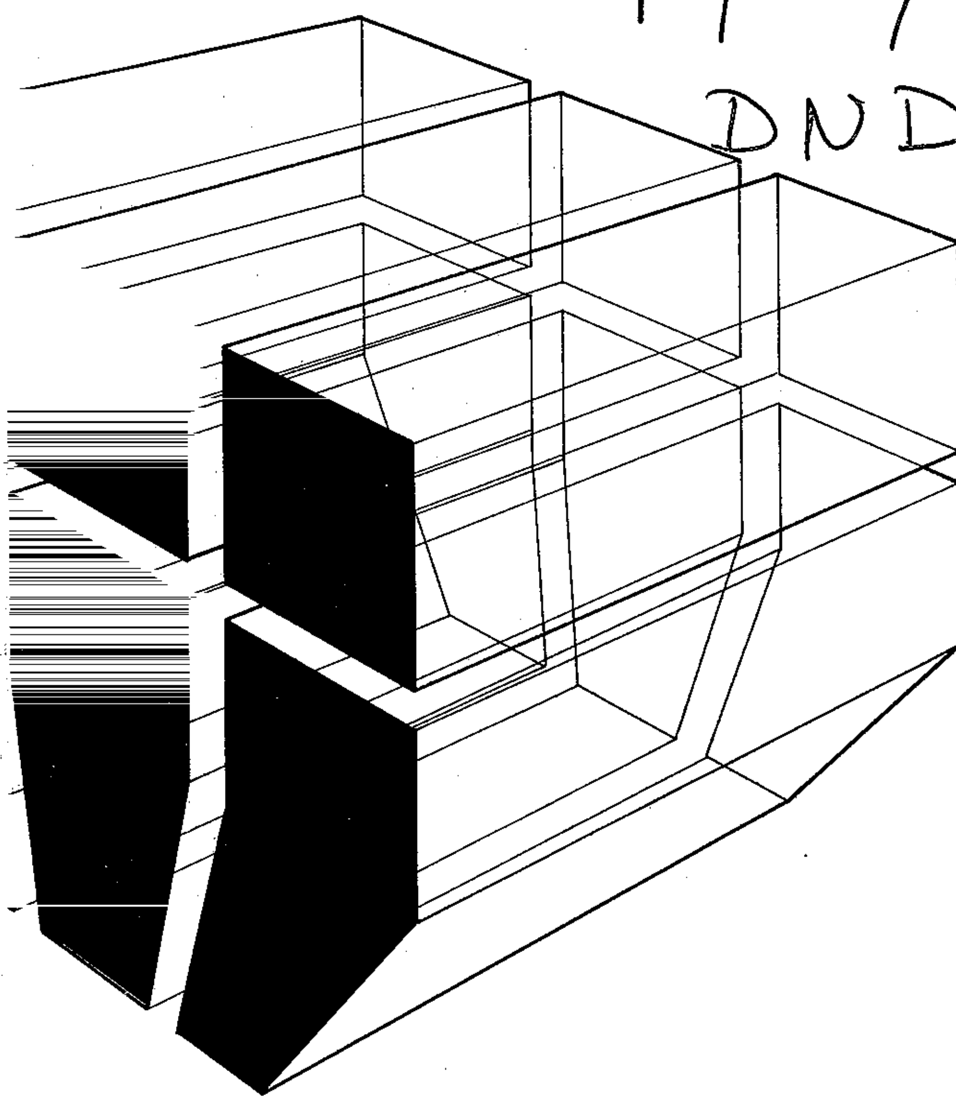
Systems Approach to Life-Cycle Design of Pavements

METHODOLOGY AND EFFECTIVENESS OF DRAINAGE SYSTEMS FOR AIRFIELD PAVEMENTS



by
Harry R. Cedergren

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This report presents the findings of a study performed to review the methodology and evaluate the effectiveness of drainage systems for airfield pavements. Official Pavement Evaluation and Condition Survey Reports were reviewed for military air bases in Continental United States and a number of foreign countries; a number of airfields in the United States were inspected (some with a Waterways Experiment Station team); and test holes were drilled into heavy-duty pavement at three airfields.

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The testing consisted of measuring the in-place permeabilities of base and subgrade materials, and recording the saturation levels within pavements in relation to rainfall events. At a fourth Field Investigation site, discharges from pipes in a "comprehensive underdrainage system" were measured in relation to rainfall events, to develop the time-lag characteristics of the drainage system.

This study indicates that most of the airfield pavements have relatively good surface drainage but slow subsurface drainage. Joint and surface sealing and repair programs are not able to keep all surface water out of structural sections. When heavy-load pavements are required to carry traffic of heavy planes while the pore spaces are filled with water, the rates of damage are often much greater than when there is no free water present, and load-carrying capacities may be lowered.

Most of the heavy-duty pavements have been conservatively designed and show little structural damage, although there are various levels of problems with shrinkage cracks, spalling, "D" cracking, joint deterioration, etc.

There appear to be definite engineering and economic advantages with types of subsurface drainage systems that are capable of greatly shortening the length of time that free water can stay in structural sections. The report makes the recommendation that such systems be considered in any major replacements and in new construction of heavy-duty pavements.

FOREWORD

This investigation was conducted as part of a program of the U. S. Army Construction Engineering Research Laboratory (CERL) to look into the total sphere of maintenance and the costs of lack of maintenance of airfield pavements and appurtenant facilities. The work was funded by the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under project 4A664717D895, "Military Construction Systems Development;" Task 04, "Military Airfield Facilities;" Work Unit 507, "Systems Approach to Life-Cycle Design of Pavements." The OCE Technical Monitor was Frank Hennion.

This report was developed by Harry R. Cedergren, consulting engineer, Sacramento, California, under contract No. DACA23-C-0025, with the Chicago District, Corps of Engineers. Principal investigator is Dr. Eugene Marvin of CERL.

COL M. D. Remus is Commander and Director of CERL and Dr. L. R. Shaffer is Deputy Director.

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METHODOLOGY AND EFFECTIVENESS OF DRAINAGE SYSTEMS FOR AIRFIELD PAVEMENTS

PART I - INTRODUCTORY

1 INTRODUCTION

Purpose of Study. This report gives the results of a project that consisted of making a study and preparing a report on the "Methodology and Effectiveness of Drainage Systems for Airfield Pavements." Part II - Section "F" of the solicitation stated that the objective of the project "is to define the various surface and subsurface drainage systems currently used with airfield pavements, to evaluate the effectiveness of the different systems, to designate the level and type of maintenance operations which must be performed on each drainage system and to evaluate the relative damage which will likely occur to the pavements if the prescribed maintenance operations are not performed."

Part II of the solicitation also stated that "In order that the most efficient and effective methods of providing pavement drainage be incorporated in future designs, and that the proper maintenance be given to existing drainage systems, existing methods of providing surface and subsurface drainage of airfield pavements should be categorized and evaluated for effectiveness. Required maintenance operations of the drainage system should be determined along with the level and frequency of maintenance activities. The effect of not accomplishing the prescribed maintenance activities on the pavement performance should also be determined."

Implementation of the Study. The first step in the project was a meeting at CERL in Champaign, Illinois, to discuss project objectives and general approaches to be used in determining the kinds of drainage systems in current use and general procedures for conducting the study. As a result of these discussions and a subsequent meeting, it was decided that the information collecting phases of the work would be carried out in several steps as follows: (1) a general review of current airfield drainage concepts and practices, (2) a study of selected pavement evaluation and condition survey reports to be supplied by CERL and loaned from other agencies, (3) site inspection trips to selected air bases and airfields (partially in the company of Waterways Experiment Station teams), and (4) field investigations, including the installation and observation of sounding wells in pavements at selected air bases and airfields.

Significant information, solutions, charts, etc. would be summarized and prepared from analysis of data and theoretical solutions to subsurface drainage conditions, and for preparing the necessary reports.

The main tasks were carried out as follows:

General Review of Airfield Drainage Practices. After the first meeting at CERL, a trip was made to Waterways Experiment Station, Vicksburg, Mississippi, where two days were devoted to talking with hydrology, hydraulic, and pavement engineers to determine their thinking about both surface and subsurface drainage and the various kinds of systems in use on Military air bases. These discussions, together with telephone calls to a number of "experts" in airport or pavement drainage concepts, led to the conclusion that although drainage design manuals of the Corps of Engineers contain criteria for designing bases with sufficient permeability to achieve 50 percent drainage in 10 days or less (after complete flooding), this method has mostly been used to design thick granular bases in frost-susceptible climates. Where pipes are provided, they are usually in drains at lower, outer edges of base courses.

Surface drainage needs are carefully analyzed, and air bases generally are provided with extensive collector and discharge sewers for removal of storm waters with little or no pondage, except for brief periods during storms.

The basic philosophy used in designing pavements is that the supporting layers under pavements must be strong and durable, and rapid drainage of water out of structural sections is not necessary under ordinary circumstances.

Study of Pavement Evaluation and Condition Survey Reports. To obtain background in prevailing practices in drainage and on the probable effectiveness of drainage methods and systems in use, approximately 60 official Pavement Evaluation Reports, Condition Survey Reports, and special reports by Waterways Experiment Station (WES) were examined in detail. Important conditions described in the various reports were summarized and tabulated. This summary tabulation is given in Appendix A, with brief statements about pavement conditions relating to drainage or lack of drainage at the various air bases.

Many of the airfields studied have pavements in a wide range of design thicknesses and pavement types; wide ranges in age, traffic volume and weight, subgrade conditions, degree of drainage, climatic conditions, state of maintenance and reconstruction; and other variable conditions. Most of the reports dealt with the more important pavements and the more significant conditions that could be rated by visual surveys. The summary in Appendix A must be looked on as a more or less "random sampling" of a very complex mass of facilities and reports, with emphasis placed on the most apparent problem areas in which water appeared to be a causative factor.

On the basis of this review of reports, it was concluded that surface drainage design and facilities are generally adequate to meet the needs, although localized problem areas are often found.

It was found, however, that excess water that accumulates within structural sections is a contributary factor in pavement distress at a majority of the airfields included in the study. Since many of the pavements studied are carrying loads much heavier than they were intended to carry, it is not surprising that problems should have developed. It also appears that the heavy-duty pavements designed for B-52 planes and their supporting fuel planes, are in excellent structural condition on the whole, although there are various levels of problems with shrinkage cracking, spalling, joint deterioration and other distress factors.

Site Inspections of Selected Airfields. During the interviews that were conducted at Waterways Experiment Station on July 17 and 18, 1972, the writer was told that WES Pavement Condition Survey teams would be making surveys at a number of bases in the next few months. Those in charge of of this work invited the writer to take part in any of these inspections that would be helpful to this study of airfield drainage. Several bases were visited with the WES Survey team. During this investigation period a municipal airport was also surveyed by the writer, where a totally failed runway-taxiway system had been reconstructed in 1969 on a "comprehensive underdrain system" (see Appendix F).

Upon returning to Sacramento after these Site Inspections, other inspections were made by the writer (without WES engineers) at several other Air Force bases.

Descriptions of the airfields visited during the Site Inspections, together with pertinent conditions noted, are given in Appendix B, Part 2. Selected photos illustrating conditions observed at the bases are given in Appendix B, Part 3, for several problem areas, as follows:

1. Surface drainage facilities and conditions.
2. Joint sealing and repair methods and problems.
3. Structural damages or weaknesses.
4. "D" cracking and spalling problems.
5. Bleeding, surging, and other signs of excess water.
6. Entrapment of water in bases on subgrades.
7. Reflection cracking through overlays.

During all of the site inspections, engineers from the Base Civil Engineer's offices provided guidance in planning the pavement inspections, helpful information about sequences of construction, age of pavements, and other pertinent information about local conditions. Generally, relatively little cost information was available regarding maintenance or replacement costs attributable directly to lack of drainage.

It is felt that the site inspections provided valuable insight into the general magnitude of the problems with water in air base pavements, and the maintenance and replacement practices at the various air bases.

Field Investigations. Under the work plan, after making a survey of the methods in use for surface and subsurface drainage of air bases and airfields, by the steps described in preceding pages, three or more airfields were to be selected by the Contractor (in consultation with CERL) for an "evaluation of the effectiveness of the various types of drainage facilities," including airfields that were rated to have "good" to "bad" drainage systems. The evaluation method was to "be left to the Contractor," but the proposed method "will be submitted to the Contracting Officer's representative at CERL for evaluation and suggestions."

After the initial surveys have been made and a draft report prepared and reviewed by CERL, airfields were selected for Field Investigations. Local conditions and other factors important to this investigation are summarized in Table 1.

Table 1

Significant Factors That Impinge on Drainage Systems at Selected Airfields

Identification	
A	Pavements subjected to high volume of heavy aircraft loads; moderate rain--in a "semi-arid" climate; impervious subgrade; joint problems with some pavements.
E	Pavements subjected to heavy aircraft loading; substantial rain and cold weather; sandy subgrade appears to provide better than average natural drainage.
F	Pavements subjected to heavy aircraft loads; extensive repairs to runway; in a heavy rainfall area.
G	Pavements subjected to large volume commercial traffic; heavy rainfall area, mild climate, clay subgrade; extensive drains under runway that was reconstructed in 1969 after prior failure of undrained pavement.

*These airfields are described in greater detail in Appendix B.

The Contractor suggested that the method of evaluation of drainage-effectiveness be to install observation wells and to record the rise and fall of saturation mounds within structural sections of selected pavements at three of the bases. Since there were no known installations of this kind, it was considered somewhat exploratory in nature, but it was felt that useful information could be obtained. It was known that wells could not be installed in busy runways, and that it would be necessary to restrict these installations to other areas, largely taxiways. It was also known that no wells could be installed at the commercial airport because of the high volume of traffic, but the drainage system under the 1969 runway-taxiway system could be evaluated by obtaining readings of outflows from pipe outlets.

Subsequently, arrangements were made with subcontractors for diamond-coring and drilling holes through PCC and AC pavements and bases for the installation of simple open-end pipe observation wells for the measurement of water levels. Three airfields were selected for this purpose. Detailed descriptions of the installation methods used, logs of all holes, and summaries of water level readings and rainfalls occurring during the period of observation, are given in Appendices C, D, and E. These reports include plain drawings showing the locations of the wells, cross sections with logs of the holes and sketches of the wells, in-place permeability test data, water level readings at various times in relation to rainfall events, and typical water profiles during the period of observation.

The fourth site selected for field investigations was reconstructed on a "comprehensive subdrainage system" after the original pavements failed very rapidly because of excess water and heavy traffic. This investigation is described in Appendix F.

Because of the extremely large volume of traffic at this runway it was not possible to physically occupy any of the pavements long enough to install observation wells; however, arrangements were made with the airport engineer for outflowing quantities from underdrains to be measured a number of times during and after heavy rainstorms. It was hoped that sufficient readings could be made at apppropriate times to develop outflow hydrographs of the subsurface drains, determine the time-lag of outflow from the system, and obtain other useful information to rate the efficiency of this system. As may be seen in Appendix F, water starts to emerge from pipes within the first hour after the start of a rainstorm, and the lag after the end of a storm may trail off for a half day or possibly more.

Reporting the Basic Findings. The basic findings of the study of various official reports, site inspections, and the field investigations, are presented in Appendices A through F of this report. Appendix A tabulates the pertinent information in the condition survey reports and pavement evaluation reports that were made available to the writer. Appendix B contains pertinent information about the bases inspected during the site inspection phase, together with selected photos illustrating a number of major problem areas that were common to essentially all airfields.

Detailed information about the field investigation sites, as already noted, is given in Appendixes C, D, E, and F. The locations of airfields investigated in the United States are given in Fig. 1.

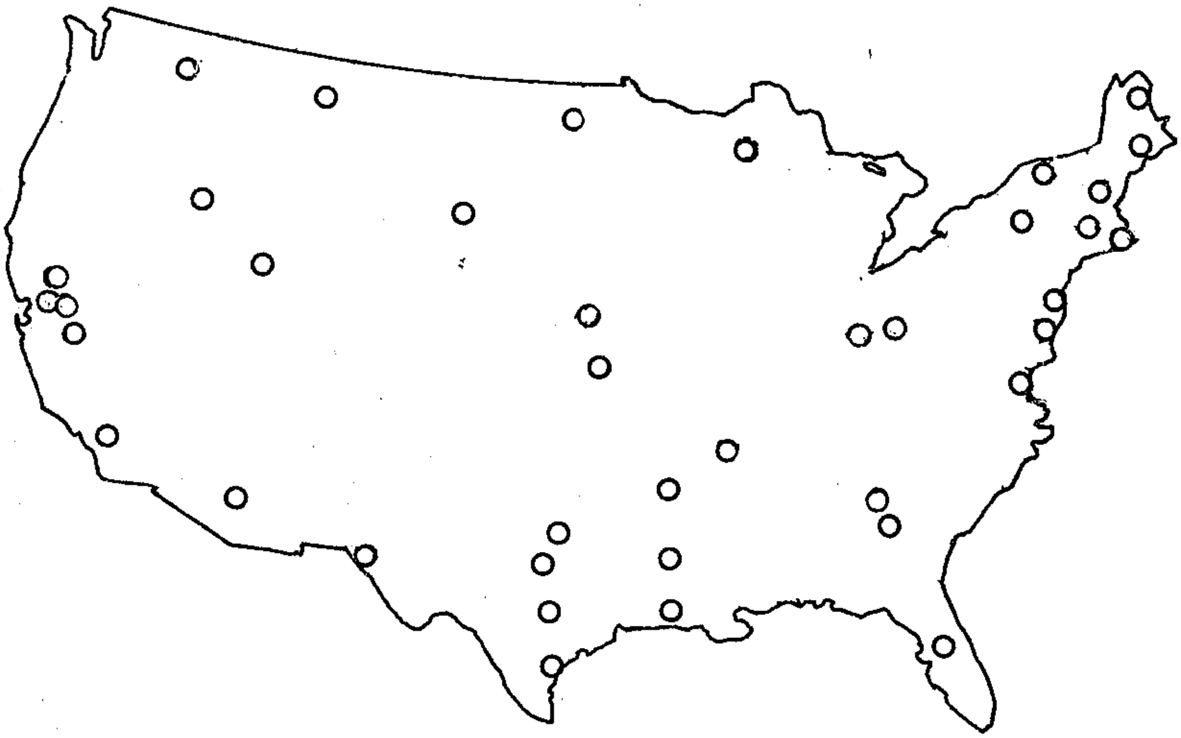

Figure 1. Locations of airfields investigated in the United States.

Interpretations of all of the information gathered in these studies are given in the basic text of this report, together with summaries and other information required in the Work Plan. Surface drainage is covered in Part II, and subsurface drainage in Part III. Kinds of systems in use are categorized and the effectiveness of the various systems is evaluated. It may be seen (Part II) that the effectiveness of the surface drainage systems is discussed in relation to basic capabilities or deficiencies for accomplishing the desired result of preventing the ponding or excessive accumulation of water on paved areas. The effects of maintenance and restoration practices on the effectiveness of surface drainage systems are discussed. Also, typical conditions relating to surface drainage that were observed during site inspections and field investigations are described.

In relation to subsurface drainage (Part III), effectiveness is rated both in terms of basic efficiency for removing subsurface water and by cost-effectiveness over the life cycle of the pavement-drainage systems.

2 WHY PAVEMENTS NEED TO BE DRAINED

Historical Comments. As long ago as 312 B.C., the ancient Romans were building roads that have lasted to this day. These road builders appreciated that stability could be maintained only by keeping the road in a relatively drained condition, and drainage ditches were part of their construction. In later centuries a number of great names stand out in the history of road building. Perhaps one of the greatest of all time was John L. McAdam, whose report to the London Board of Agriculture[1] has often been quoted. In part, he said: "The roads can never be rendered thus perfectly secure until the following principles be fully understood, admitted, and acted upon, namely, that it is the native soil which really supports the weight of traffic; that whilst it is preserved in dry state it will carry any weight without sinking . . . that if water pass through a road and fill the native soil, the road whatever may be its thickness loses support and goes to pieces . . . ."

A civil engineering handbook published in 1932[2] says, "Water in one form or another on or beneath the road surface is the greatest enemy to a stable and permanent road structure." With the development of rational methods for designing pavements this concern over environmental conditions such as the amount of water that can fall on and infiltrate into pavements has been of less concern to most pavement designers. In 1962 one leading pavement designer said that if laboratory tests of subgrade strengths are

[1] John L. McAdam, *Report to the London Board of Agriculture* (1823).
[2] Thomas R. Agg and Ralph A. Moyer, *Highways*, Section 4, "General Engineering Handbook," edited by C. E. O'Rourke (McGraw-Hill Book Co., 1932), p. 353.

made on materials while in a saturated condition, there should be no need for the introduction of some kind of numbers to express a regional factor (that conclusion is considered by the Author to be a serious error).

It is known that traffic impacts can be much more severe on pavements that are filled with water than the same impacts when these pavements are in a relatively dry state. Some of the accelerated traffic tests conducted by the Corps of Engineers produced much greater rates of damage during periods when free water was present than when it was not. This was also true of highway tests. For example, an analysis of the AASHO road test in Ottawa, Illinois indicated damages were 10 to 40 times greater during wet periods than dry. Highway Research Board Special Report 22, in 1955 stated that analysis of damages during the WASHO road test in Idaho indicated rates of damage as much as 70,000 times greater during the "worst" periods than during the "best."

Tests by Barenberg and Thompson[3] in a circular test track gave damages 100 to 200 times greater when test structural sections contained free water than when they contained no excess water.

Regardless of what criteria are used for designing pavements, it is known that slowly draining sections are damaged at faster rates than rapidly draining sections, and that effective drainage can extend the useful life of essentially every pavement. The key question becomes "How much is returned in service per dollar expended for pavements having drainage systems of various capabilities?" This question is the subject in Chapter 9 under the heading, "Cost-Effectiveness of Subsurface Drainage Systems."

A description of some of the kinds of damages that can be caused by free water in structural sections is presented next.

<u>The Detrimental Actions of Water in Pavements</u>. As the water content of subbases and bases of pavements increases toward 100 percent saturation, important reductions in supporting power can occur. Once complete saturation is reached, and all of the void spaces and cavities are filled with water, a number of very severe actions can then take place:

1. Buoyancy by submergence reduces the effective unit weights of granular materials.

2. Traffic impacts produce water hammer actions and pulsating pore pressures which can have a number of detrimental side

[3] Ernest J. Barenberg and Owen O. Thompson, *Behavior and Performance of Flexible Pavements Evaluated in the University of Illinois Pavement Test Track*, Highway Engineering Series No. 36 (University of Illinois, January, 1970).

effects, such as:

(a) Mud pumping and erosion of subgrades and bases, resulting in loss of support to both rigid and flexible types of pavements.

(b) Squeezing of mud and other fines into incipient cracks in the bottom side of AC pavements, leading to accelerated deterioration and failure.

(c) Disintegration of stabilized bases such as CTB.

(c) Pressure concentrations on subgrades.

3. Formation of water pockets at interfaces between pavements and bases and between bases and subbases, with loss of bond.

4. Freezing of the water in pores or at interfaces, or in cavities, with accompanying frost damage.

5. Shrinkage cracking of AC pavements.

These actions are described in more detail in the following paragraphs.

Free water or "excess" water in structural sections is probably responsible for at least 80 percent of the structural damages to pavements in the author's opinion. Figure 2 shows a pavement that has been severely damaged by excess water, and extensively repaired. Figure 3 is a photo of a heavy duty PCC pavement in a "semi-arid" climate, with poor subsurface drainage. Although surging or bleeding is evident, the strength of the pavement has been sufficient to resist structural damage. When the free water level rises to or near the top of a pavement, it creates a condition of buoyancy, thereby reducing the effective unit weights of the materials to half or less of the drained unit weights. This reduces frictional resistance substantially below the levels with no buoyancy.

Probably the most severe effects of free water are those of the traffic impacts which produce transient pore pressures that tend to move the water about and also produce pulsating pore pressure waves going into and out of the supporting layers. Only when free water is present can the particles be forcefully moved about, producing erosion at interfaces between pavements and bases, etc. When traffic is predominately in one direction, as with most highways, the jet-like actions at the interfaces cause the progressive movement of base materials (even when stabilized) from beneath leading slabs to the under edges of trailing slabs, frequently with some material being forcefully ejected from joints and cracks. As used here, a trailing slab is one just preceding a cross joint, and a leading slab is one just beyond the cross joint. The progressive movement of material leads to the common faulting or step-off that is so disconcerting to users of the pavement system. If not corrected, it magnifies the

Figure 2. Photo of a poorly drained PCC pavement that has been severely damaged by excess water, and extensively repaired.

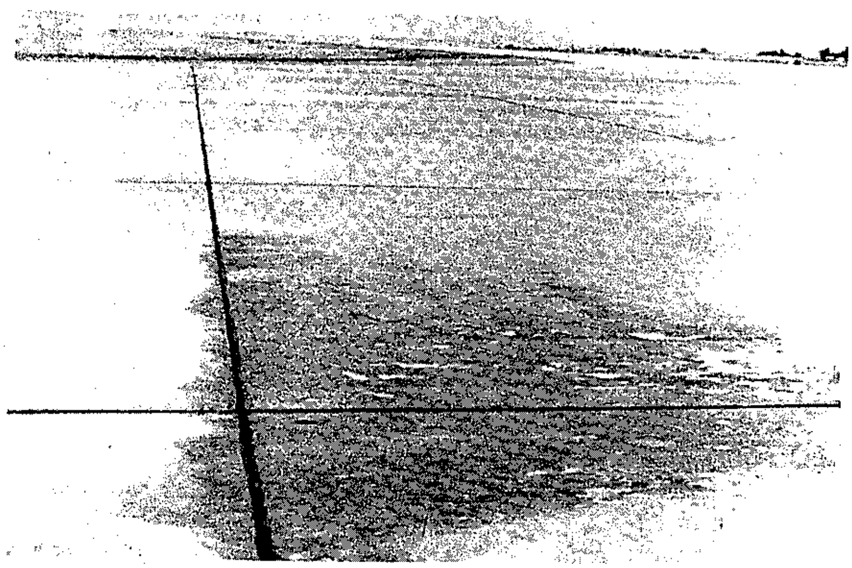

Figure 3. Photo of a poorly drained, heavy-duty PCC pavement in "semi-arid" climate; stains indicate possible bleeding or surging; no apparent physical damage yet.

pounding on the pavement and eventually leads to serious cracking and ultimately total failure of entire slabs[4].

On airfield pavements where the direction of traffic alternates to some extent, the faulting may not be evident, but cases have been reported where large losses of material by pumping have resulted in a dished-in condition of slabs, with ultimate structural failures requiring complete reconstruction of entire pavements (runways, taxiways, etc.).

Even though most of the heavy-duty pavements examined in this study showed little or no physical damage, evidence of possible weakening effects of heavy wheel loads pounding on trapped water in structural sections was seen at a number of the fields inspected. At two of the field investigation sites, B-52 loads evidently produced pore pressures of sufficient magnitude to create a "quicksand" effect in the pea gravel backfill placed in the bottoms of observation wells installed under this project. These forces caused the pea gravel to rise several inches or more in some of the wells in a period of one or two months. Oscillating pore pressures of such magnitudes may be responsible for significant reductions in subgrade support and major reductions in pavement life from reduced support, in the judgment of the author.

Pulsating pressures in the free water in structural sections can force mud, cement slurry, etc. into fine cracks in AC pavements, preventing the self-healing of such cracks. The water movements can cause stripping of asphalt from stabilized bases and subbases. They can lead to the complete disintegration of cement-treated bases and can cause overstressing of subgrades.

If the bond between successive lifts of AC or between AC pavements and their bases becomes broken and water gets in, transient water pressures can cause separation of the layers with the formation of bulges, or the physical "break-out" of chunks of pavement. This action is probably responsible for the majority of the "chuckholes" that develop in pavements. It occurs most rapidly during or immediately after heavy rains.

When free water can remain within pavements for extended periods (because of slow drainage), this increases the opportunities for freezing and the resulting frost damages. Rapid drainage of water out of structural sections after inflows from rains, melting ice and snow, etc. could greatly minimize such damages.

Some investigators have concluded that shrinkage cracking of AC pavements is aggravated by prolonged exposure to free water. Another type of disintegrating damage, "D" cracking in PCC pavements is thought to be greatly increased by the slow drainage of water out of pavements in regions

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[4] D. L. Spellman, "Faulting of Concrete Pavements," *Highway Research Record 407* (Highway Research Board, 1972).

where this phenomenon is prone to occur. Verbeck, et al[5] point out that "D" cracking of concrete pavements constructed with poor quality aggregates ". . . is initiated when atmospheric moisture penetrates open joints and cracks, and together with moisture already present beneath the pavement, raises the degree of saturation of the coarse aggregate to a critical level." They say that ". . . D-cracking is caused by stresses generated during the freezing of critically saturated coarse aggregate particles." Under conclusions, this PCA report says, "Laboratory studies of pavement cores from selected locations on I-71 revealed the importance of the availability of moisture to the pavement slab and the nature of the coarse aggregate in the development of D-cracking."

The comments in preceding paragraphs outline some of the major types of failure and disintegrating action that can take place only when free water is present, or that are aggravated by free water in structural sections. It is considered evident that if pavements were designed and built as rapidly draining systems, most of these damages would be greatly reduced and the life expectancy of pavements would be increased. Almost always when pavements are failing or deteriorating rapidly, there is evidence of excess water being present.

Some types of damage, such as the erosion and pumping of material out from under pavements, can occur only when free water is there in sufficient quantity to transport solid particles or move them out of exits. Since pavement deterioration is caused by the combined effects of many factors, it is not always possible to isolate the dominating factor. Thus, when airfield taxiways or aprons fail, it is usually attributed to "overloading," excessive "tracking" of planes in confined paths, "underdesign" or some other directly obvious factor.

Although the rate of damage with excess water present often can only be guessed in relation to each "dry" load application for any given pavement, it is likely to be rather substantial for many pavements. Some pavements that have deteriorated rapidly from "overloading" or "tracking" might not have been so severely damaged if the accumulation of free water could have been prevented. The potential benefits of building pavements that will drain rapidly can be largely in one of two forms: (1) increased load-carrying capacity, or (2) increased pavement life.

The Severity Factor of Wheel Impacts on Flooded Structural Sections. Maintenance forces are the busiest during periods of heavy rainfall and the

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[5] George Verbeck, Paul Klieger, David Stark, and Wilmer Teske, *Interim Report on D-Cracking of Concrete Pavements in Ohio*, Agreement No. 1910, Ohio Dept. of Highways with Portland Cement Association (PCA), Research and Development Laboratories, Skokie, Illinois (March, 1972).

spring thaw, as these are the times that structural sections contain the most free water. And, it is during the times that free water is present in pavement structural sections that wheel impacts do their greatest damage. In this discussion the term "severity factor" is used to express the relative damages caused when free water is present in pavements as compared with the damages occurring when little or no free water is present. It is the ratio of the average cumulative damages per load application during these two periods of time.

Assigning values to the severity factor for specific pavements is often difficult because insufficient records are customarily kept of pavement damage versus traffic applications and climatic conditions. But, records of several experimental pavements have been examined in detail by engineers who studied these experiments, and a number of useful interpretations were found that are believed helpful. When the amounts of damage to the AASHO road test and the WASHO road test were examined, short periods of time in the spring break-up were compared with the rates of damage during the best time of the year, and relative damages were found to be hundreds to thousands of times greater during the worst periods than during the best. When comparisons were made for broader periods of time, the differences were often in the range of 10 to 40 (see Table 2). It should be noted that base course and subbase materials in the WASHO road test were frost susceptible.

The tests by Barenberg and Thompson[6] in the University of Illinois circular test track, using materials similar to those used in the AASHO road test, are believed highly significant. In test set No. 1, approximately 700,000 applications of a 3200-lb wheel load were made on the as-constructed pavements with little or no distress apparent beyond moderate traffic compaction. The water table was then raised to the level of the pavement surface and the pavement was flooded for 6 days by sprinkling, during which time no loads were applied. After 6 days of flooding, the pavement surface was drained and the water table lowered to about the mid-height of the pavement base course, and the loading applications were then continued. Almost immediately, distress began to show up, and the dynamic testing had to be terminated after 12,000 additional load applications because of severe pavement roughness and excessively deep rutting. For this test series, each wet load application was equivalent to at least 200 "dry" applications in the amount of damage produced.

Ideally, similar information should be obtainable from the records of behavior of airfields and other pavements in service. But, little factual data about rates of deterioration or maintenance costs are kept for actual pavements in service. As noted above, the detailed records for some experimental test pavements indicate that the presence of excess water in

[6] Ernest J. Barenberg and Owen O. Thompson, *Behavior and Performance of Flexible Pavements Evaluated in the University of Illinois Pavement Test Track*, Highway Engineering Series No. 36 (University of Ill., Jan., 1970).

Table 2

Severity Factors for Flooded vs Drained Structural Sections

As Estimated from Published Reports

Test	Reported By	Behavior Reported	Severity Factor
WASHO Road Test	HRB Special Report 22, 1955.	During period of worst damage (the frost melt period), the rate of distress averaged 748 sq ft/day for 12 load applications/day, and in period of least damage, the rate of distress was 1.0 sq ft/day for 1173 load applications/day.	70,000:1
AASHO Road Test	W. J. Liddle, page 40, Proceedings, First International Conf. on Structural Des. of Asphalt Pavements, Ann Arbor, Michigan, 1962.	Damaging effects of traffic were more severe in Spring frost melt period than in Summer and Fall. Road Test data suggest that a "Regional Factor" of 0.3 to 1.5 be applied to load applications on dry roadbeds (Summer and Fall) and 4.0 to 5.0 for loads applied to saturated roadbeds.	Working value between 10:1 and 40:1 (Author's estimate)
University of Illinois circular test track	Ernest J. Barenberg and Owen O. Thompson, Report dated January, 1970.	In test set No. 1, 700,000 load applications (3200 lb load on single tire) produced 0.2 inch to 0.5 inch rutting of unsaturated roadbed; after saturation, 12,000 additional applications of same load destroyed the pavements (0.5 inch or more additional rutting).	200:1

structural sections can greatly accelerate the rate of damage, and greatly reduce the life cycle. In a discussion of the findings of the AASHO road test, Barenberg[7] points out that "Nearly 90 percent of the loss in serviceability of flexible pavements in the AASHO road test occurred during the three months immediately following the spring thaw." He says that although many highway engineers have believed that the loss in serviceability was due to a reduction in subgrade strength, a review of test data has shown that ". . . the moisture content of the subgrade during the spring of 1960 was 14.6 percent and during the summer of 1960 was the identically same value of 14.6 percent. Thus the loss of serviceability for the flexible pavements could not be attributed to saturation of the subgrade." He also points out that during that same period the moisture content in the granular base course varied from 4.3 percent in the spring to 3.6 percent in the summer of the same year. These findings, together with the findings of tests on flexible pavements at the University of Illinois, lead to the conclusion that ". . . minor changes in the moisture content of granular base and subbase materials can have a substantial influence on the behavior and performance of pavements." Under "Practical Applications," Dr. Barenberg says, "Every load applied when the degree of saturation of the base and subbase is high will have a much greater effect on pavement performance than those applied when the degree of saturation is low. Thus, <u>it is imperative that the moisture be drained from the base and subbase layers as rapidly as possible</u>. <u>Since the time required to drain horizontal layers is a function of the square of the length of the flow path, it is important that the flow paths be kept as short as possible</u>."

The Summary Report (Report 7) of the AASHO road test[8] says that ". . . the studies disclosed that all failures of rigid pavements were preceded by pumping of material from under the concrete slabs." As already noted, pumping of material out of cracks and joints does not occur unless there is free water present to carry the solids.

When severe damages occur during even small percentages of the time each year, the "life-cycle" of a pavement can be drastically shortened. The influence of increased structural damage during various amounts of time that sections contain excess water each year can be easily demonstrated by simple arithmetic calculations which weigh the relative severity factors of wet and dry load applications. Charts are readily developed to show the importance of the various factors (see Fig. 4). Thus, if excess water is present 10 percent of the time, and wet applications are 10 times as severe as dry applications (S = 10), the resulting effect of 90 percent "dry" applications and 10 percent "wet" applications is 90 x 1.0 + 10(10) = 90 + 100 = 190, and the effective <u>rate</u> of deterioration is 190/100 = 1.9 times that of all

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[7] Ernest J. Barenberg, *Behavior and Performance of Aggregate-Soils Systems Under Repeated Loads*, Highway Engineering Series No. 43 (University of Illinois, August, 1971).

[8] *Special Report 61-G*, The AASHO Road Test, Report 7, "Summary Report" (Highway Research Board, 1961).

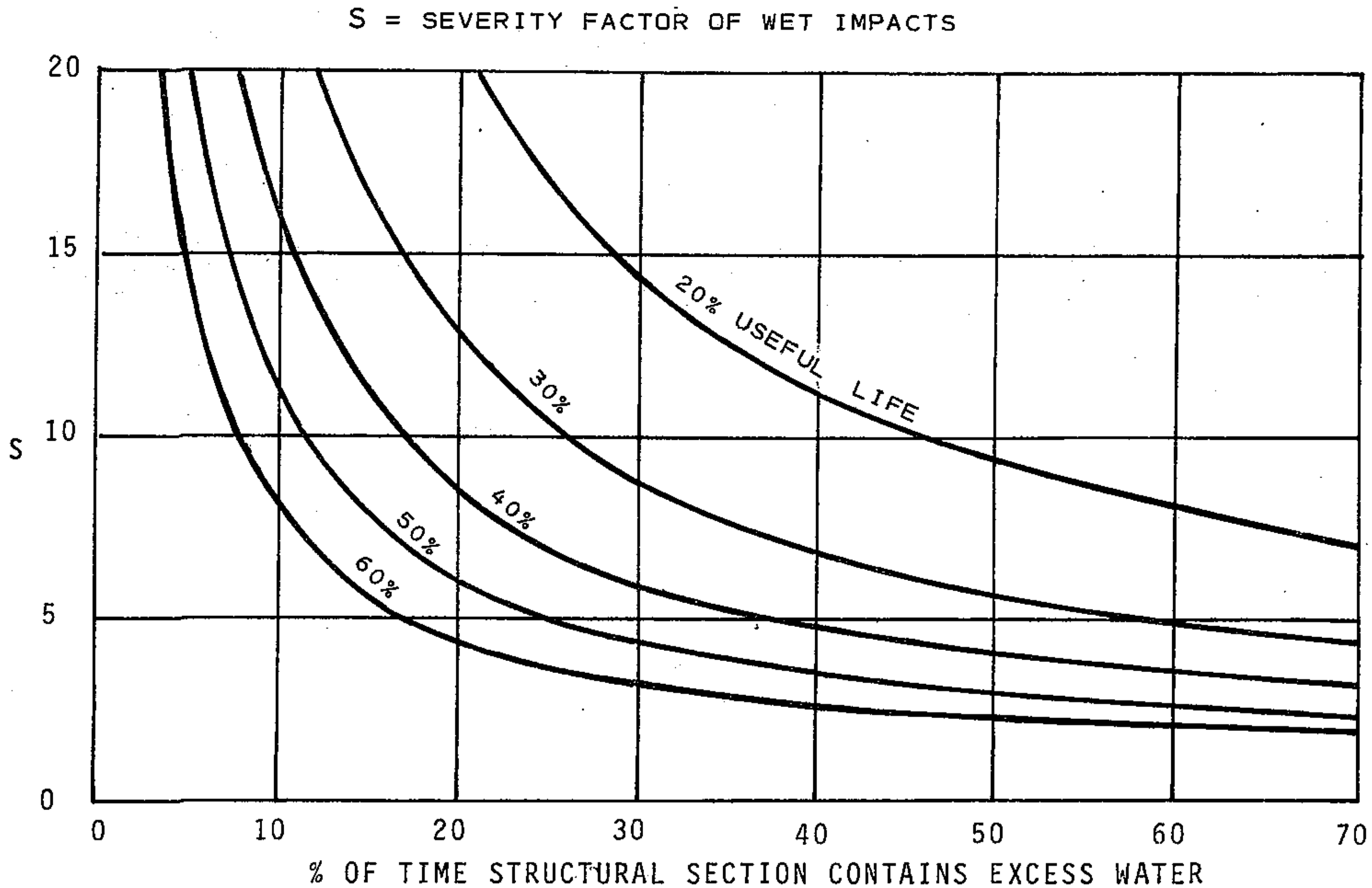

Figure 4. Chart showing effect of excess water on life-cycle of pavements.

applications being made with no excess water present. For these assumptions, the amount of useful life of this pavement would be (100/190)(100) = 53% of the potential life cycle of a perfectly drained pavement. Using this method of calculation, Fig. 4 was prepared for severity factors up to 20 and for exposures to excess water varying from zero to 70 percent of the time. Curves are given for amounts of useful life that can be expected for various severity factors and percent of time structural sections contain excess water. It can be seen that wet impacts have the potential for greatly reducing the length of effective life of a pavement.

Another illustration of the potential harm of allowing heavy-duty pavements to carry loads while filled with water is given in the following paragraphs, which show the effect of reduced subgrade support (due to any cause) on load-carrying capacity.

The Effect of Reduced Subgrade Support on Pavement Performance. When structural sections contain excess water, there appears to be a possibility that an effect of the free water may be to cause a reduction in the subgrade reaction over that which would exist if there were no excess water to be acted upon. Presumably, the standard design charts fully take into account any and all effects of water in pavement structural sections, including those just mentioned. Design charts provide a way to obtain an approximate evaluation of the effects of any factor, such as the presence of excess water, on the load-carrying capabilities of given total thickness pavements.

To relate the potential effects of altered subgrade reaction, Figures 5 and 6 were prepared. Figure 5 has curves of required pavement thickness

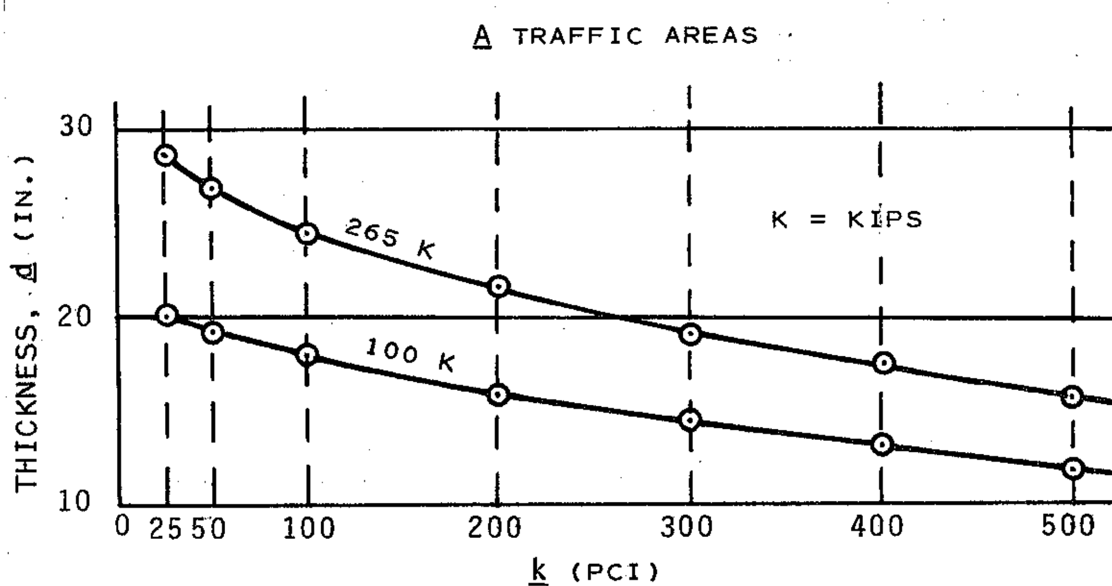

Figure 5. d versus k for 710 psi flexural strength concrete.

d versus subgrade reaction k for 100,000-lb gear loads and 265,000-lb gear loads (from *Technical Manual TM 5-824-3* , Department of the Army, and the Air Force, December, 1970). All determinations from the design charts are for flexural strengths of 710 psi and A traffic areas. The 100,000-lb gear load is for twin wheels spaced 37 in. c.c. and 267 sq. in. contact area each wheel (this is from Fig. 2, p. 8 of the Manual). The 265,000-lb gear load is for twin-twin wheels spaced 37 x 62 x 37 in. c.c. and 267 sq. in. contact area each wheel (this is from Fig. 3, p. 9 of the Manual). In this plot (Fig. 5) it is apparent that for a given thickness of PCC pavement, the allowable gear load varies substantially with the subgrade reaction.

Figure 6 was also plotted from the data in Figures 2 and 3 of the referenced Technical Manual. On Fig. 6, load-carrying capacity versus k was plotted for various thicknesses of 710 psi flexural strength PCC. This figure can be used for estimating what additional or reduced wheel loads

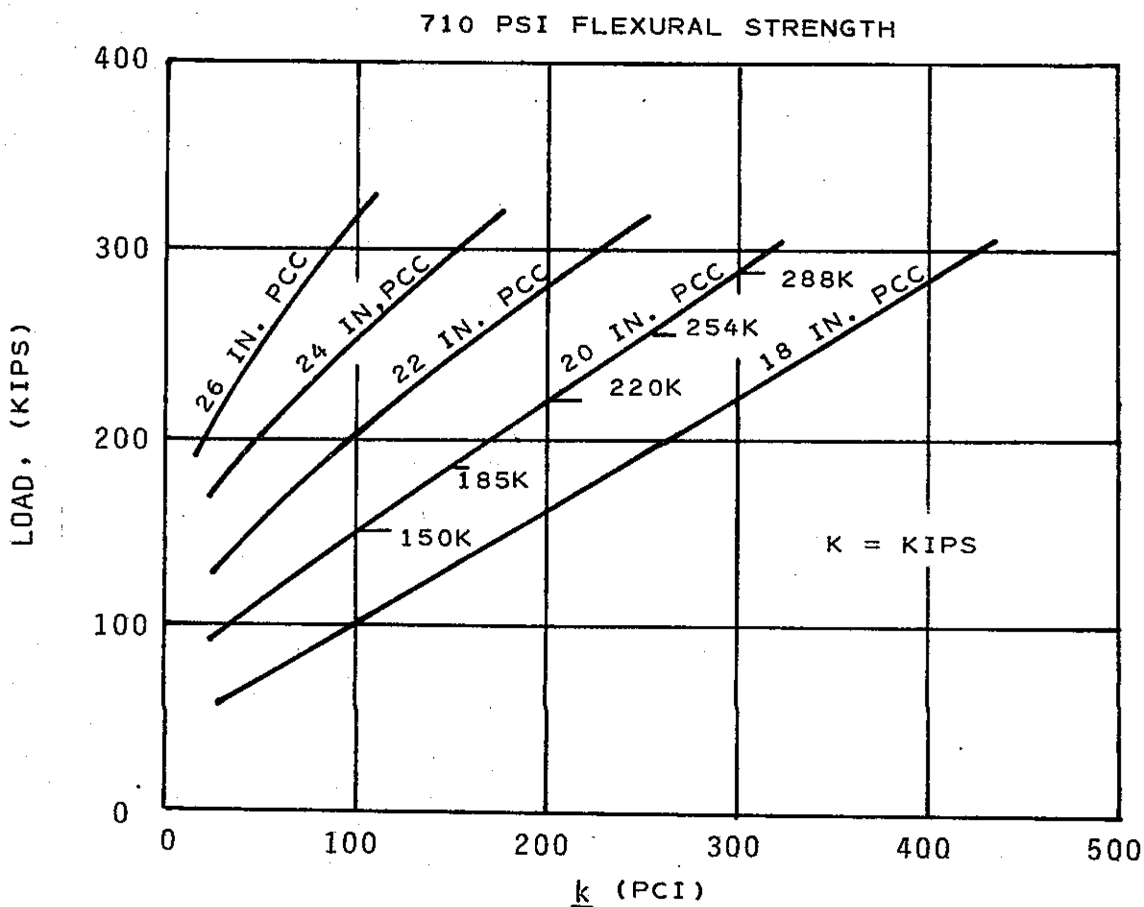

Figure 6. Load versus k for various PCC pavement thicknesses.

can be supported if an effective subgrade reaction k were for any reason smaller or larger than expected in design. For example, if a 20-in. thick PCC pavement had been designed for a k value of 200, the allowable gear load would be 220 kips (220,000 pounds). But, if the effective reaction were 150, the allowable gear load would be 185 kips or a reduction of 16 percent. If the effective reaction were only 100, the allowable load would be 150 kips, or a reduction of 32 percent.

Now, if for any reason (such as increased drainage efficiency) the effective subgrade reaction is larger than assumed, how much additional load could be allowed? In this example, if the effective reaction were increased from 200 to 250, the allowable gear load would be increased to 254 kips for an increase of 15 percent; and if the reaction were 300, the allowable load would be 288 kips, which is an increase of 30 percent. It is apparent that only slight increases in effective subgrade reaction can substantially increase the sizes of the loads that can be carried by pavements.

Another, perhaps more direct measure of the benefits of preventing losses in pavement support by any factor such as the dynamic impacts of heavy planes on sections filled with water, can be obtained by analyzing the relationships between "subgrade reaction" and the theoretical number of plane load coverages to failure.

Figure 7 was prepared from CERL computer calculations which relate fatigue failures of PCC pavements with subgrade reaction for 20-inch, 22-inch, and 24-inch thick pavements. Figure 7, prepared from the fundamental relationships for stresses produced by the gear loads of B-52's, assumes a design life which permits 10,000 coverages to failure. Examination of this plot indicates the following subgrade reactions are required for pavements of the assumed thicknesses:

PCC thickness	Required subgrade reaction, k, pci
20 in.	300
22 in.	210
24 in.	115

Since "coverages to failure" diminish with reductions in the effective subgrade reaction, Fig. 7 offers the means for predicting reductions in useful life, caused by reductions in subgrade reaction, below those presumed in a design analysis. Such determinations are summarized in Table 3, which gives potential reductions in coverages to failure caused by unanticipated reductions in subgrade reactions of 25, 50, and 75 pci for PCC pavements having thicknesses of 20, 22, and 24 inches. The data indicate that even a moderate reduction in effective subgrade reaction, k, can have a large effect on the number of coverages to failure.

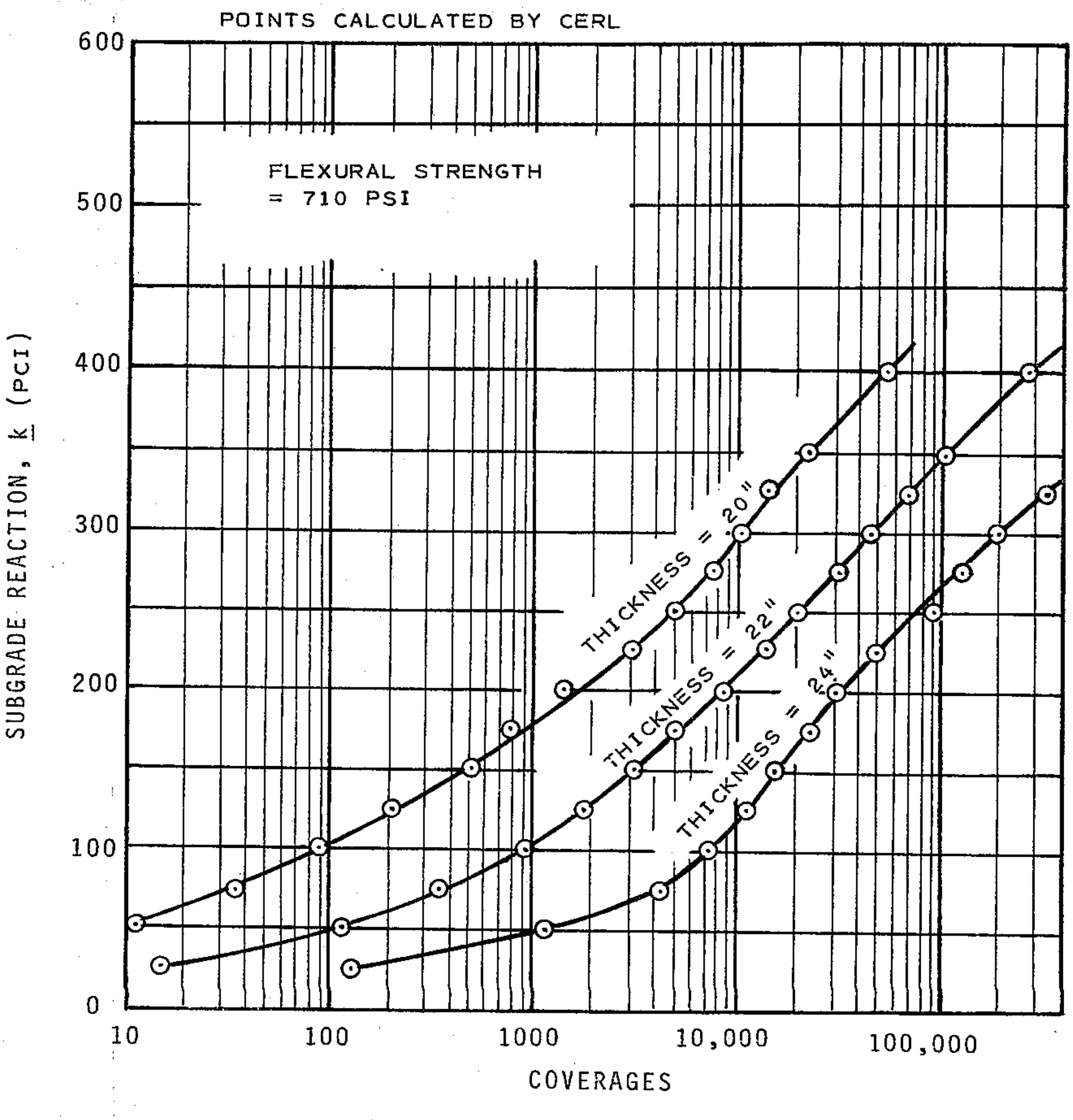

Figure 7. Coverages of B-52 aircraft to initial failure of PCC pavements.

Table 3

Potential Reductions in Coverages to Failure Caused by Unanticipated Reductions in k

Thickness of PCC	Subgrade k needed for 10,000 Coverages	Reduction in Coverages Caused by Unanticipated Reductions in k of: 25 pci	50 pci	75 pci
20 in.	300	20%	50%	70%
22 in.	210	40%	60%	78%
24 in.	115	40%	75%	95%

These relationships suggest that if any factor (such as rapid drainage of pavements) would appreciably increase the subgrade reaction (or prevent reductions in it), fairly substantial amounts of money could be spent on the necessary systems for the same total initial costs as pavements without this added protection.

One of the runways studied was reconstructed on a comprehensive subdrainage system with 16 miles of pipe drains under a ballast course (see Appendix F), at an added cost of less than 5 percent of the total cost of this job. This drainage system rapidly removes the water that leaks through the joints and cracks in the PCC pavement. It will very likely more than double the useful life of this runway. Yet, if it only extended the useful life by one year, the small added cost would be more than recovered: The pavement that it replaced cracked up very rapidly in 1969, largely from a lack of drainage.

<u>Summary Comments</u>. Although putting a dollar value on the cost of not providing rapid drainage for pavements is not always easy, a large amount of fundamental knowledge has been gathered that points to the fact that pavements are damaged significantly more when they carry traffic with free water present. It appears that any slightly greater costs that would be needed to provide rapid drainage of important pavements (at the time they are constructed) could be repaid many times over in trouble-free service and extended life.

PART II - SURFACE DRAINAGE

3 SURFACE DRAINAGE SYSTEMS CURRENTLY IN USE

Basic Principles. The purpose of airfield drainage as defined in an official manual is to quickly remove and dispose of any water which "may hinder any activity necessary to the safe and efficient operation of the airport." Drainage systems should collect and remove surface water runoff from each area of an airfield, remove excess underground water, lower the water table, and protect all slopes from erosion. Criteria for designing surface drainage systems for airfields are given in a Department of the Army Technical Manual[9] and a Federal Aviation Administration Advisory Circular[10], which have both been consulted in the preparation of this report.

Principles of hydrology are used in determining rates of flow off paved and non-paved areas comprising the areas draining into inlets and other facilities for removal to safe distances from airfields (see Fig. 8). The intensity of the design storm may be either 2 years[9] or 5 years[10], depending on the agency setting the standards. The degree of protection provided a specific facility depends primarily upon the importance of the airfield, as determined by the mission and volume of traffic to be accommodated, the necessity for uninterrupted service, and similar factors. Within certain limits the degree of protection increases with the importance of a given airfield, but minimum requirements must be adequate to avoid hazards in operation of the airfield.

Temporary ponding is usually permitted on graded areas adjacent to and between runways and taxiways (see Fig. 8). Usually no ponding is allowed on runways, taxiways, aprons, or other paved areas. When determining the extent of ponding to be permitted, careful consideration is given to insure that ponding basins conform to allowable grading criteria and that possible damage to pavement subgrades and base courses because of occasional flooding will be kept to a minimum.

The principle upon which surface drainage of paved or unpaved areas works is that water flows over the areas by sheet flow or overland flow, to inlets or ditches at safe distances from paved areas. In turn, these facilities take the water far enough away from the paved areas for safe

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[9] *Technical Manual No. 5-820-1; Air Force Manual No. 88-5,* Chapter 1 (Headquarters, Department of the Army and the Air Force, 31 August, 1965).

[10] *Airport Drainage,* Advisory Circular 150/5320-5B, Department of Transportation (Federal Aviation Administration, July, 1970).

areas. The basic criterion for buildup of sheet flow on pavements is to prevent safety hazards to the aircraft. Thus, it is more critical to keep the film thickness down on runways than on taxiways and aprons. Fortunately, the dimensions of the various pavements tend to aid in keeping the buildup smaller on the more critical pavement areas.

Components of Surface Drainage Systems. The integral parts of the surface drainage systems, in addition to the slopes and runoff characteristics of the various components of paved and non-paved areas that allow the water to escape by overland flow, are: (1) the inlets which allow the water to get into the conduits, (2) the conduits which conduct the water underground to safe distances, (3) open channels that pick up the water and take it away from the airfield, (4) manholes, lamp holes, headwalls, and other structures that are needed for the continued operation and maintenance of the systems, and (5) erosion control facilities that prevent the movement of soil that would clog inlets, conduits, or channels.

Inlets. Normally, inlets that are located in non-paved areas are at least 75 feet from the edges of the pavements; and they are located at low points so they will effectively collect the water. The permanent ponding of large areas is not permitted at inlets; however, localized ponding sometimes occurs when the land settles below the lip of an inlet, or an inlet is placed at too high an elevation. Suitable grates are provided for inlets, to prevent the inflow of material that can clog the pipes. When inlets are located in paved areas, such as in the interior of aprons or within any heavy-load pavements (see Fig. 9), grates and frames are

Figure 9. Photo of a grated inlet in a large operational apron; has large inflow capacity.

removal in open ditches, or if necessary in additional conduits.

The motivating force for the flow of water over airfield areas is produced by the downslope component of the force of gravity, which increases in direct proportion to the steepness of the slopes of these areas. Effective water removal requires the use of the steepest safe slopes. To avoid the formation of "birdbaths" and to ensure positive drainage, bituminous types of pavements should have a minimum slope of 0.015 in the direction of overland flow, and rigid pavements should have a minimum slope of 0.010. To minimize problems caused to aircraft using airfields, the slopes are kept as flat as possible, and sometimes are less than those recommended for optimum drainage. The use of flat slopes increases the time required for water to drain from large paved areas, and increases the amount of time water is available to soak into porous pavements, leak into cracks, etc.

Dividing large paved areas into smaller sub-areas would increase the speed of drainage; however, the Army Manual[11] specifies that "Pocket or waffle-type drainage patterns, consisting of closely spaced interior inlets in pavements with intervening ridges are to be avoided." It points out that ". . . this type of surface grading causes aircraft taxiing problems including porpoising and possible bumping of wing tanks." Also, it says that "Although center-crowned, rooftop, or 'turtle-back' grading patterns generally result in most economical drainage, adjacent pavements or topographic considerations often necessitate other types of pavement grading, including 'valley' or 'W'-type patterns."

To reduce turf encroachment and facilitate drainage at pavement edges, the use of a steepened transition shoulder section immediately adjacent to airfield pavements is permitted. The 10-ft strip of shoulder adjacent to pavement edges should have a 5-percent slope.

Since runways are relatively long and narrow structures, the predominating direction of flow is to the sides, more or less normal to the axis. Parking aprons, on the other hand, are usually large in extent, and must be drained away from hangars and other buildings serving the aircraft, as well as away from taxiways and other service areas. Aprons may be drained entirely toward one end or side in a single sheet flow, or they may be divided into a number of large sub-areas with the water being fed to one or more lines of inlets located at the centers of the sub-areas.

Paved areas at airfields are usually placed slightly higher in elevation than adjacent land areas, and the shoulders and land areas have steepened slopes to facilitate the quick removal of water from the paved

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[11] *Technical Manual No. 5-820-1; Air Force Manual No. 88-5*, Chapter 1 (Headquarters, Department of the Army and the Air Force, 31 August, 1965).

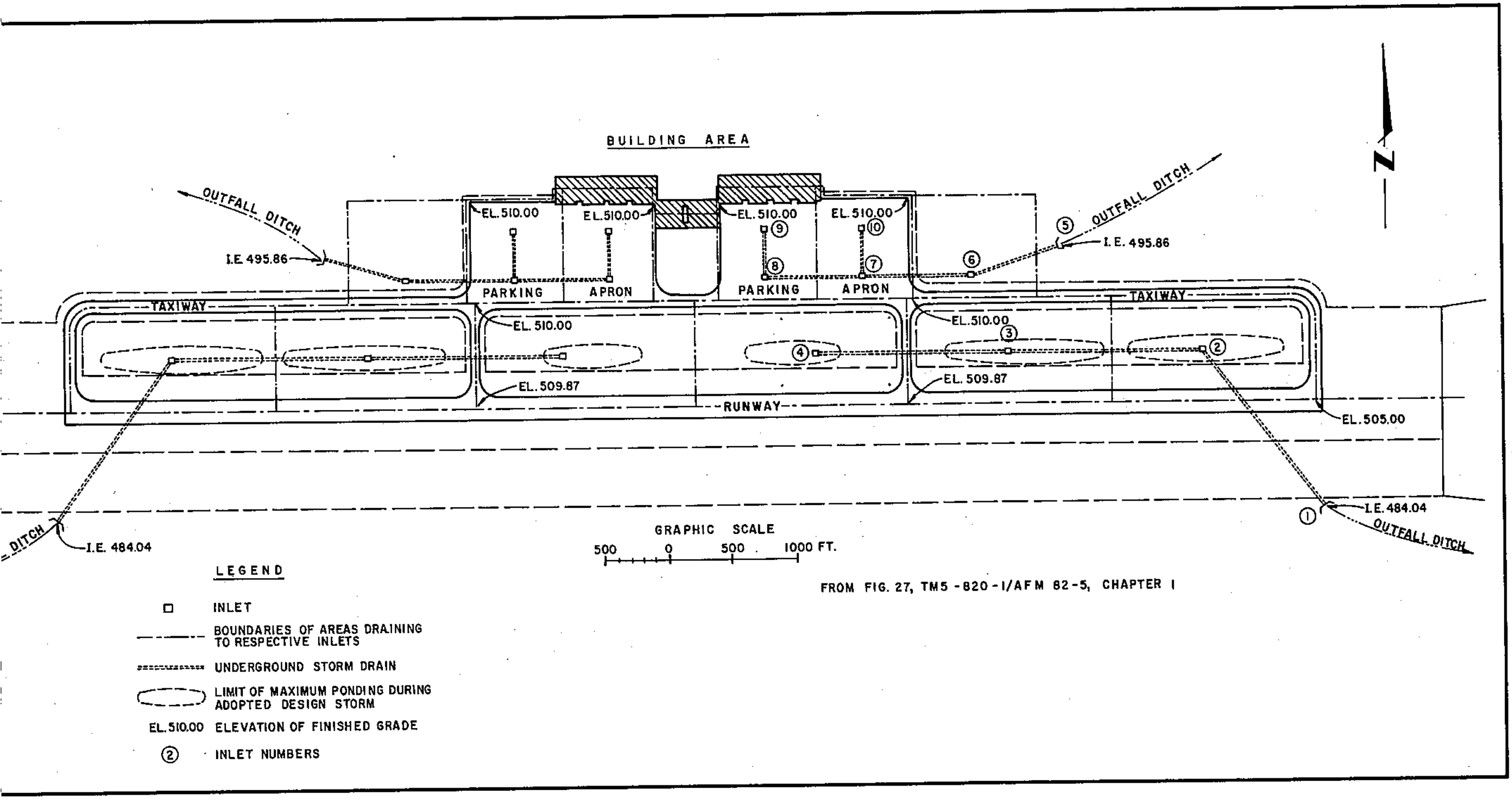
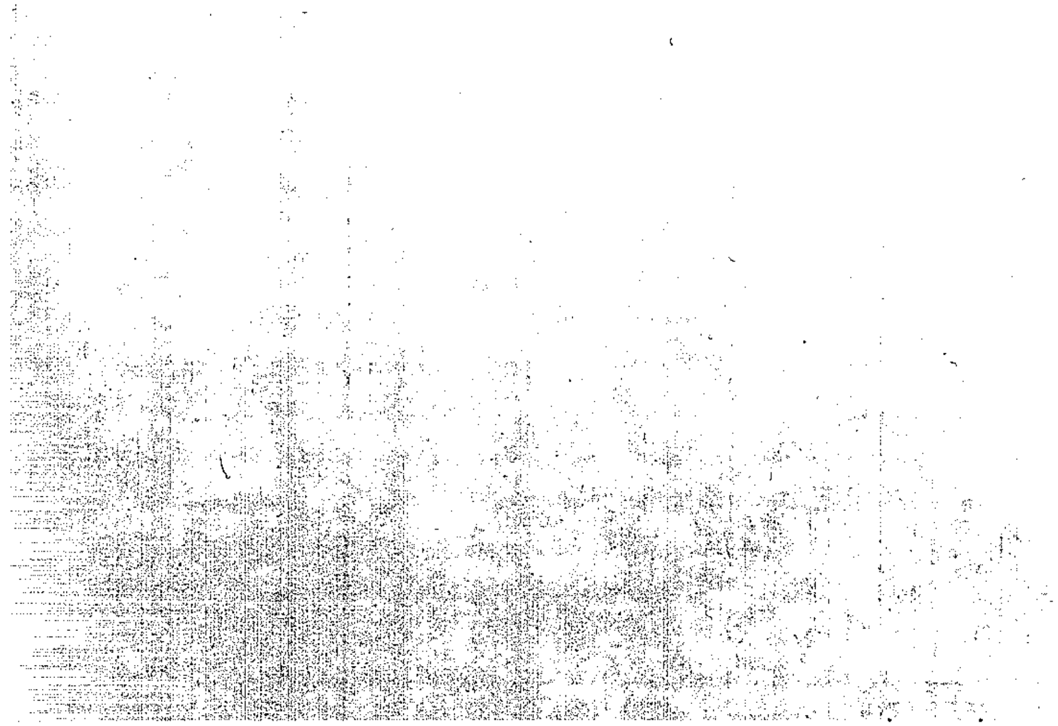
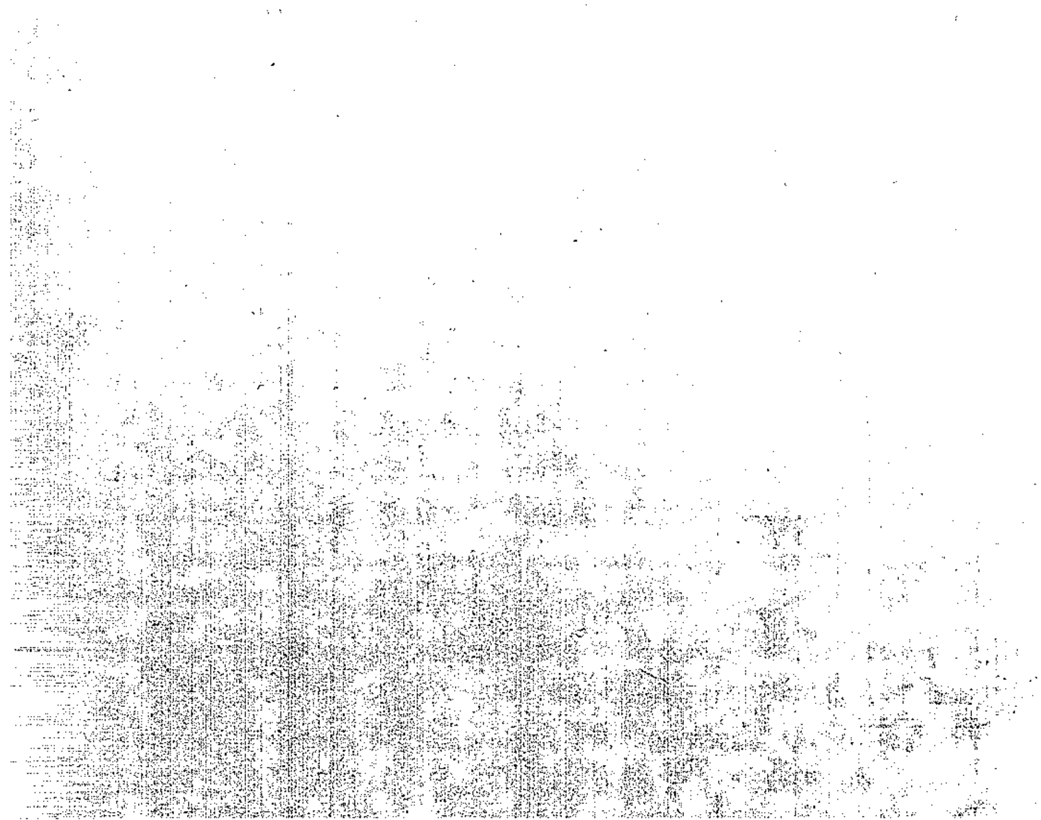


Figure 8. Sample layout of primary storm drainage system.





designed to have sufficient strength to support the weight of aircraft which will use the facility. Since these loads may be much greater than those of trucks and other maintenance vehicles, special grates often may be required. They are designed to be of sufficient size to have the required inflow capacity.

Conduits. All pipes in an airfield drainage system are designed to have sufficient capacity to remove the flow without excessive ponding. Conduits used for airfield drainage systems may be constructed of conventional standard sizes of pipes, provided with either bell-and-spigot or tongue-and-groove joints in precast pipes, adequate metal bands for corrugated metal pipes, and couplings for asbestos-cement pipes. Tests usually are made to determine if the chemical characteristics of the water and soil might have an adverse effect on the pipe, and a type selected that is the least affected by the chemicals in the water and soil.

Joints are made sufficiently tight to prevent the intrusion of the adjacent soil, which might clog the pipes and reduce their discharge capabilities. Any pipes that are to be placed under traffic areas are designed to have sufficient strength to serve without damage from the imposed loads. In areas that are not subjected to heavy traffic, cast-in-place concrete pipes may be utilized.

Drain outlets are located where they will best serve the needs of the drainage system.

Open Channels. Open channels are designed with side slopes that meet safety criteria. They are protected against erosion where necessary, and are chemically treated where necessary to prevent excessive grass or brush growth.

Miscellaneous Structures. Manholes, lamp holes, headwalls, and other structures that are needed for the operation and maintenance of airfield drainage systems are generally similar to those used in municipal construction, but special structures are designed whenever needed. When located in usable areas of airfields, structures are not permitted to extend above the adjacent ground or paved area. In land areas, the tops of such structures usually are designed to be one- or two-tenths of a foot below the ground line, to allow for possible settlement around the structure. Any structures that may be traveled upon by aircraft or other vehicles are designed to have sufficient strength to serve their purpose without damage.

Erosion Control Facilities. Non-paved areas over which water will flow in airfield drainage systems are treated, where necessary, to prevent excessive soil erosion, as sheet erosion of large areas of erodible soils can produce sufficient quantities of silt or other fine soil to impair the capabilities of drainage inlets, conduits, channels, etc.

Typical Systems in Use. Figure 8 shows a typical layout of a surface drainage system for a portion of an airfield. Taken from *TM 5-820-1*, it shows the basic features of surface drainage systems designed in accordance with the principles outlined in this section (see page 31).

Several of the photos in the Appendixes show typical surface drainage features at air bases visited during Site Inspections and Field Investigations.

The typical crowning of primary runways, taxiways, etc., to facilitate surface runoff is illustrated in Figures B-1 and B-2 (Appendix B), which are low, cross-views of pavements. Even when positive slopes are designated into pavements, if the slopes are very flat as on many parking aprons, sheet flow on these large, paved areas can build up to 1/2 inch and more in depth during moderately heavy rainfalls, and it may take hours for the water to flow off after it stops raining. Figures C-14 and C-15 (Appendix C) show water standing about 1/2 inch deep on a pavement several hours after a rain.

Some of the older pavements were built on very steep cross slopes to speed up surface drainage. One such pavement (see Fig. B-19, Appendix B), developed very serious structural problems and serious joint problems because of slow subsurface drainage, showing that steep surface slopes alone, although beneficial in removing surface water, may have little influence on subsurface drainage.

When positive slopes built into airfield pavements are lost because of traffic compaction, settlement, or other factors, water may stand for prolonged periods in the depressions that form. Figure B-3 (Appendix B) shows such an area on a taxiway adjacent to an apron.

High sod at the edges of pavements, which is very common at airfields in rainy climates, can impede the flow of water from these pavements. Figure B-4 (Appendix B) shows a low view along the edge of one of the parking aprons noted during the Site Inspection trips. In areas of low rainfall, little or no grass grows near pavement edges or on the slopes around inlets, as shown by Fig. B-7 (Appendix B) of the slope between an inlet and a taxiway.

Many, if not most, airfields have some pavements where the surface geometrics and low grades combine to cause water to collect and drain away very slowly. The most common areas where such problems were noted during the field trips were at sag-vertical curves, on parking aprons, and at the intersection of runways and taxiways. Figures C-14, C-15, and C-17 (Appendix C) show some areas of this kind where surface drainage was relatively poor.

All of the air bases visited in this study had grated inlets feeding surface runoff into storm sewers. No detrimental problems either from surface clogging of inlets by grass, or other debris, or harmful siltation of storm sewer pipes, were reported at any of the air bases visited, although minor problems are fairly common. Figures B-5, B-6, B-7, and B-8 (Appendix B) show some of the inlets observed during Site Inspection trips.

In the design of air bases, engineers make detailed computations to determine the discharges that need to be handled by surface drainage systems. Relatively good systems were provided at all of the bases studied. It appears that all of these systems are performing essentially as assumed by the designers.

4 EFFECTIVENESS OF THE SURFACE DRAINAGE SYSTEMS

Basic Considerations. The continued effectiveness of surface drainage systems depends on the permanent maintenance of their water-removing capabilities. How well any system functions is measured by its effectiveness in preventing the accumulation of water on paved areas, adjacent shoulders and land areas, and in effectively removing water away from the air base. The effectiveness of surface drainage systems is readily apparent, as any significant deficiencies are out in the open where they can be seen (see Fig. 10). In contrast, the effectiveness of subsurface drainage systems is less obvious to those not familiar with the tell-tale signs discussed in other parts of this report.

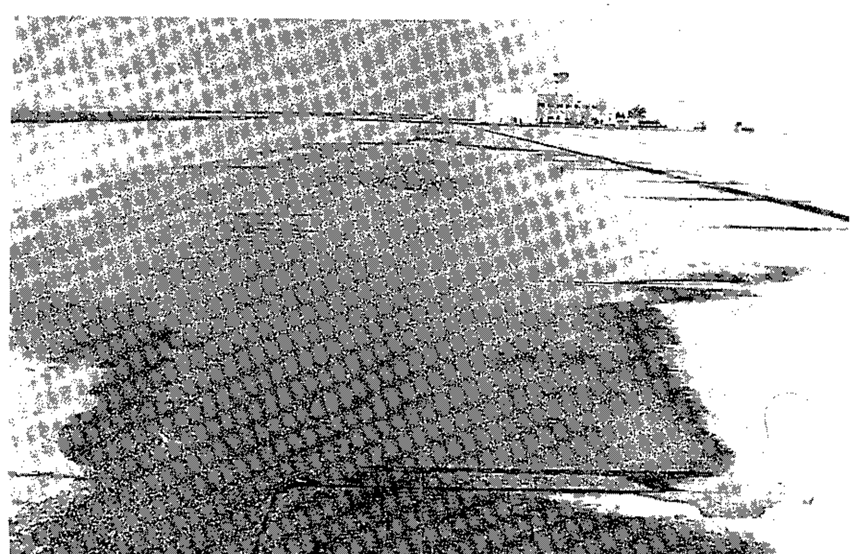


Figure 10. Photo showing large "birdbath" in a wide, flat pavement.

Slow surface drainage of water from paved areas adds to the total exposure of pavements to excess water, although poor subsurface drainage often is a much greater retarding factor. For example, assume that an airfield has 30 significant rainfalls a year, and that water remains on some poorly drained areas one day after each rainfall. Then, the total exposure to surface water is 30 + 30 = 60 days each year. Now, assume that joints and cracks in the pavements allow free access of surface water into the structural section, and that the subgrade has a coefficient of permeability of 3×10^{-6} cm/sec (0.01 ft/day). If the average hydraulic gradient discharging water into the subgrade is 0.20, it will take approximately 30 days for 50 percent drainage of the base after each rainfall (see Fig. 28). For these conditions, the structural section could contain harmful levels of free water essentially 100 percent of the time, and the primary benefit of good surface drainage would be in reducing the quantities of water that can enter into the structural section, and thus aid in keeping the saturation level down in the section.

In cases where subsurface drainage is more rapid than in this example, improved surface drainage could be much more beneficial in reducing total time of exposure to free water. If the time for 50 percent base drainage were 3.0 days (subgrade $\underline{k} = 3 \times 10^{-5}$ cm/sec = 0.1 ft/day), the total exposure to excess water , in this example, would be 60 + 3.0(30) = 60 + 90 = 150 days. Then, for perfect surface drainage, the total exposure to surface water would be reduced by 30 days, for an overall reduction of (30/150)(100) = 20 percent, which could be significant.

Regardless of the kind of subsurface drainage provided, it is important that the quantities of surface water inflows be kept to lowest practical minimums. For this reason, it is important that efforts be made to maintain good surface drainage, and to keep all important pavements sealed as well as is practicable.

How well the surface drainage systems have worked at bases inspected during the Site Inspection phase of this project and during the Field Investigation phase, is illustrated by selected photos presented in Appendixes B, C, D, and F. They are discussed in subsequent parts of this section.

Effect of Maintenance and Restoration Practices on Surface Drainage. The way that maintenance of pavement surfaces and major reconstructions and other activities can influence surface drainage is described in the following paragraphs, as based on information gathered in this study.

Partial Overlays, Surface Seals. If overlays, seals, or armor coats are placed on lower slopes of paved areas, they can impede drainage and serve as water traps. To prevent the entrapment of water, all such surface treatments should be extended to the crown of the pavements being treated, or they should be feathered out to fill the depressions that would trap water.

Keel Sections and Other Restorations. When damaged central sections of taxiways, runways, etc. are dug out and restored by heavier keel sections, any losses in grade can be corrected, and thus surface drainage can be improved. Where such repairs had been made at the bases inspected during the field phases of this project, excellent restorations of grade had been accomplished, providing not only stronger pavements but better surface drainage as well.

Joint and Crack Sealing. Those responsible for maintaining important pavement systems usually have continuing programs underway to try to keep joints and cracks sealed as well as possible, even though the effective sealing of joints and cracks is extremely difficult. Thermal expansion and contraction of pavements inevitably leads to the opening of construction joints, and the formation of shrinkage cracks in most pavements. These actions tend to cause joint and crack seals to break loose or open up after varying periods of time. The present state-of-the-art does not ensure watertight joints long after construction or after sealing under maintenance, and water can enter most pavements in spite of all efforts to keep them tight. Nevertheless, good joint and crack sealing programs can reduce the volumes of water that can get into pavement structural sections. It therefore is felt desirable to try to keep all types of important pavements sealed as well as possible.

Grated Inlets, Outlet Pipes, Etc. All grated inlets and all conveyors of surface water from important airfield pavements must be kept free of debris, silt, or any matter that can impede the flow of water (see Fig. 11). Periodic checking of the freedom of all of these facilities for conducting water is an important part of the activities of base civil engineers.

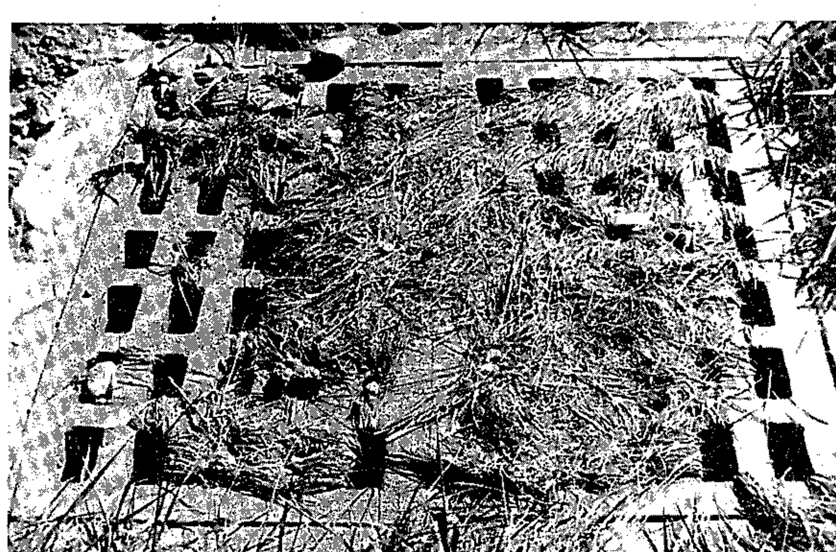


Figure 11. Photo showing common type of clogging nuisance at inlets; requires periodic cleaning by maintenance forces.

While the silting of pipes has been a serious problem at some airfields, it was not reported to be of consequence at any of the bases visited in this study.

High Sod and Grass at Pavement Edges. When sod and thick grass growth are allowed to develop at the edges of pavements, surface drainage can be severely impeded. Usually, when water stands, it is at outer edges, and this many not be damaging to wide runways; however, it was said to be a factor in the premature destruction of one major runway-taxiway system at a commercial airport. It did not appear to be a major cause of pavement damage at the military air bases inspected in this project, although it might have been a contributing factor in some cases. Figure 12 shows an example high growth along the edge of a taxiway.

Figure 12. Photo showing high sod at the edge of a taxiway having poor subsurface drainage, and poor surface drainage at outer edges.

Hydroplaning Prevention Treatments. In recent years, extensive efforts have been made to improve the skid resistance of air base pavements during heavy rainstorms by the cutting of transverse grooves with diamond saws[12,13,14]. Also, some use has been made of overlays of the so-called

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[12] "Diamonds Groove Runway for Skid Resistance," *Roads and Streets* (Dec.,1967).
[13] "Runway Tests Utilize Grooving," *Aviation Magazine* (June 17, 1968).
[14] Vernon R. Gingell, "Grooving the Runway at Washington National Airport *Civil Engineering (ASCE)* (January 1969) pp. 31-33.

"popcorn" AC mixes for the same purpose[15]. A primary benefit of both of these treatments appears to be in increasing friction. The hydraulic conductivity of the relatively small slots from diamond grooving (1/8 x 1/8 in. to 1/4 x 1/4 in., spaced an inch apart), is not considered beneficial in removing surface water and may direct it to cracks and joints (see Fig. 13).

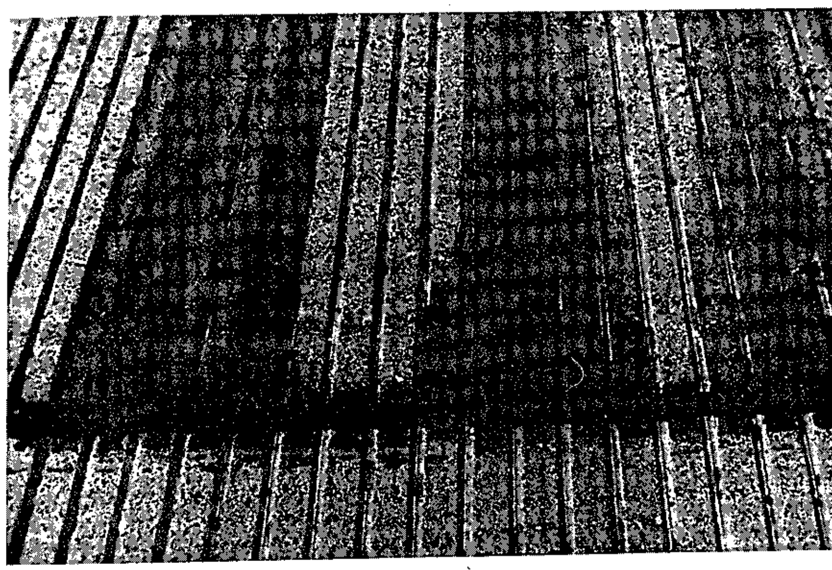

Figure 13. Photo showing diamond-grooved PCC runway; dark stains show that past inflows have entered the construction joint.

It is the opinion of the author, based on his observations, that the use of the pervious "popcorn" AC mixes for thin overlays to increase skid resistance may tend to increase the time of retention of water on some pavements, as water usually flows faster over the surface of a pavement than through the interstices of these open-graded mixes. Long after normal AC pavement surfaces have become dry after showers, he has seen water bleeding out of the edges of these popcorn overlays.

<u>Summary of Conditions Observed during Site Inspections and Field Investigations</u>. Important types of conditions influencing the overall effectiveness of surface-subsurface drainage systems for air bases and airfields, as observed during the site inspection phase of this project, have been described and illustrated in the preceding paragraphs and also in Appendix B. Other conditions that were noted during the field investigation phase

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[15] Michael P. Jones, "Friction Overlay Improves Runway Skid Resistance," *Civil Engineering (ASCE)* (March, 1973) pp. 45-48.

are described in Appendixes C, D, E, and F.

The primary pavements at most of the air bases visited have good cross slopes that facilitate the flow of surface water from these paved areas, although nearly every air base has some wide, flat pavements on which water accumulates to depths of 1/2 inch or more during heavy rainstorms. The surface geometrics at intersections of taxiways with runways, for example, also create conditions which tend to cause water build up during periods of heavy precipitation.

High grass and sod which impedes the flow of water from pavement edges and increases the retention time and the total exposure to surface infiltration was also observed at a number of the airfields visited. This condition can also be seen at virtually every commercial airfield in heavy rainfall areas throughout the country.

Grass and other debris had accumulated over grated inlets at several of the fields visited. When this occurs, ponding on adjacent land areas increases, but this does not cause flooding of pavements if the storage volume is sufficiently large. Unobstructed inlets of adequate capacity obviously facilitate the quick removal of surface water from important areas.

As noted elsewhere in this report, base civil engineers are cognizant of the need to maintain positive surface drainage, and try to keep joints and cracks in important pavements well sealed. Continuous programs are underway at most bases to try to accomplish this objective. Also, where losses in grade had occurred due to overloading or consolidation of bases or subgrades under concentrated traffic, keel sections had usually been removed and replaced with stronger, thicker pavements. When this was done, positive surface grades were usually restored.

5 LEVEL AND TYPE OF MAINTENANCE OPERATIONS REQUIRED ON SURFACE DRAINAGE SYSTEMS

Paved Areas. The smooth, unbroken flow of water off paved areas is essential to the effective performance of the total drainage systems. If "birdbath" or other low areas have developed because of settlement or rutting under traffic, water accumulates in these areas, increasing the quantity of water that can soak into porous pavements (not the popcorn AC mixes), or enter through joints or cracks. Any such areas should be brought back to grade to prevent further damage to the pavements. With AC pavements, thin feathered overlays can usually be placed to correct these problem areas. But, with PCC pavements, the correction is more difficult. Feathered epoxy-sealed fills have been used at a number of air bases. At others, various forms of pavement lifting by the injection of asphalt or other cementing mixtures have been used with various degrees of success. If extensive rutting is occurring, the pavement is probably being overloaded and may require a heavy overlay or complete replacement with a thicker pavement. If water is associated with these problems, it would be desirable to provide positive underdrainage in any areas that are to be extensively repaired or reconstructed.

Joint sealing programs, overlays, and other maintenance operations should not be allowed to produce high areas or ridges that will impede natural drainage.

Joint sealing programs should be initiated before cracks and joints become excessively wide, and efforts should be made to keep all heavy-load areas well sealed to minimize the entry of water into structural sections. Reduction of the volume of water that can enter into pavements should be given a high priority in maintenance programs.

Inlets. Periodically inspect all inlets for breakage of grates, elevation of lip relative to adjacent land, and for sedimentation, or accumulations of weeds, paper, or other debris which can block the entrance. Keep inlets always in good repair and free of any material that can impair the inflow of water.

Conduits. Periodically inspect for buildup of sediment from erosion of soil from unpaved areas over which water flows to reach the inlet and conduit. Also, inspect for infiltration through joints or cracks along the conduit, and for broken or collapsed pipes. Clean and repair as required to maintain the design section. Correct any unsatisfactory condition that persists.

Ditches. Periodically inspect for buildup of sediment from erosion of side slopes or from other unpaved areas over which the water flows to reach the ditch. Remove excessive vegetation and use weed killers as required to control the growth of weeds, brush, etc. that can reduce the discharge capacity of the ditch. Look for signs of gullying or sheet erosion in the slope or adjacent soil areas. If erosion is occurring, take the necessary measures to correct any damaging effects that have occurred and to prevent further erosion. Examine for evidence that waterways are too small and need enlarging.

Miscellaneous Structures. Periodically inspect all auxiliary structures such as manholes, lamp holes, headwalls, catch basins, drop structures, and any other structures needed for the continued operation and maintenance of drainage systems for breakage, blockage, settlement, undermining, or other damage; and repair, replace, or enlarge, as required for the full, effective use of the system. Look for restrictions in flow due to faulty or inadequate design, and have any deficiencies corrected when they are first found rather than wait until serious damages occur.

6 DAMAGES LIKELY TO OCCUR IF MAINTENANCE IS NEGLECTED

Placing a dollar value on the damage caused by neglect of maintenance is very difficult, as little data are usually available for such an evaluation. But, the kind of damages that have been noted in this study are summarized, as follows:

Pavement Surface Grades Disrupted or Blocked. Disruption of surface drainage occurs if for any reason the slopes in the direction of flow are altered. Some conditions that cause disruption of flow are the following: (1) low areas within pavements caused by compaction of the subgrade or any of the supporting layers of the pavement, (2) low areas or adjacent heaved areas caused by deformation of the subgrade or structural section.

Rutting in wheel paths can cause water to become trapped, increasing the quantity of water available to soak into the structural section, thus reducing the load-carrying capabilities of the base and subgrade, and causing further rutting, in a continuing cycle. A number of non-traffic actions can also disrupt surface drainage. Some of the more common are: (1) encroachment of sod at edges of paved areas, (2) the buildup of wind-blown soil at the pavement edges, and (3) placement of AC or other overlays above the original grade on the slope of a pavement.

Any disruption of flow off paved areas aggravates the problems of maintaining pavements in good condition, as this increases the length of time water remains on the pavements, and is therefore available to soak into the structural section through cracks, and joints. This is a compounding factor that accelerates the damages to pavements.

Joints and Cracks Not Sealed. Experience has shown that it is not possible to keep joints and cracks perfectly sealed for long periods of time, and some water will eventually enter. Nevertheless, efforts should be made to regularly seal joints and cracks, as this can reduce the quantities of water than can enter. Well-sealed joints may sometimes cut inflows down to 1/3 to 1/5 of the amounts that would enter wider cracks and joints. This is about the equivalent of increasing the drainage rate of the structural section by 3 to 5 times. Since the damaging effects of water in structural sections are about proportional to the amount of water that can get in, good sealing programs are considered definitely worthwhile. Even when the pavement design includes complete, effective subdrainage systems, good maintenance of cracks and joints should be continued to avoid the possibility of overtaxing the drainage systems. It is felt that good sealing programs might extend the useful life of many heavy-load pavements by several years.

Blockage of Inlets by Silting, Lack of Cleaning, etc. A lack of periodic inspections of drain inlets can lead to the complete blockage of inflows into conduits. If leaves, grass, and other foreign matter are not periodically removed from inlet grates, severe ponding over outlets can occur during heavy showers and storms. Cases have been observed where progressive accumulations of silt from erosion of the adjacent soil areas have completely filled and covered drain inlets. At one air base, the inlets had been covered for years, and the current personnel were not even aware that inlets had been installed. By carefully examining construction drawings, and prodding and digging, a system of inlets was uncovered. This is probably a most unusual case; but partial clogging of inlets no doubt is a fairly frequent occurrence.

Lack of maintenance of inflow capabilities of inlets can lead to undesirable pondage in the areas between pavements or adjacent to pavements. If the inlets are within parking aprons, actual flooding of the pavements can occur. The net result is possible increased hazard to the aircraft, together with increased saturation and weakening of subgrades and bases of pavements.

Blockage of Conduits by Infiltration, Silting, etc. Any loss of cross section of conduits by accumulations of silt or other matter within the pipes reduces discharge capacity, and cuts down the efficiency of the system. Minor amounts of sediment in large diameter pipes may be unimportant, but large accumulations can be definitely harmful, and must be avoided. Material can enter conduits by the erosion of soil on unpaved areas, or by infiltration through cracks in pipes, or through open joints. Some cases have been reported where large masses of sediment have entered into conduits, greatly reducing their capacities. When important amounts of sediment are entering into conduits, the material should be removed, and the causes of the problem should be corrected. If these matters are not corrected, severe pondage is likely to occur during heavy storms, with increased hazards to using aircraft, and saturation and weakening of bases, subbases, and subgrades at outer edges of pavements.

Blockage of Ditches by Silting, Vegetation, etc. Non-lined ditches often become clogged with heavy weed growth, long grass, brush, etc., which can greatly reduce the channel capacity. In addition, heavy sheet erosion or gullying of soil in the slopes or adjacent soil areas can cause heavy silting of the bottoms of ditches. All contributary soil areas should be planted with grasses that are native to an area or are found to be suited to given climatic and soil conditions; or otherwise treated to prevent erosion. Ditch slopes should be flat enough to resist erosion, and should be planted with low-growing grasses, or otherwise treated. Ditches should be kept free of long grass growth, brush, and other growths that could inhibit flows in the ditches.

If ditches and contributary areas are not frequently inspected and the necessary corrective work done, this can reduce the outflow capacity and lead to excessive pondage. While blockages of ditches may often be less damaging than lack of proper attention to pavements and facilities immediately contiguous thereto, ditches are still important, and should be given periodic attention.

Damages to Miscellaneous Structures. Drop structures, inlets, manholes, and other appurtenant structures can be structurally damaged if their foundations are undermined by surface erosion or internal piping. Settlement of any of these structures due to any cause, can interrupt the normal flow of water and reduce the efficiency of drainage systems.

PART III - SUBSURFACE DRAINAGE

7 FUNDAMENTAL CONSIDERATIONS IN SUBSURFACE DRAINAGE

General Discussion. Subsurface drainage is often looked upon as a qualitative problem with general solutions, when in reality it is a quantitative problem with specific solutions for individual situations. Thus, a given pavement can accept a certain specific amount of inflow through its network of cracks, joints, porous areas, etc., and at a given time its subgrade is capable of draining certain, specific quantities of water.

Water can enter into pavements from a number of sources such as (1) by flowing downward through porous or cracked surfaces, open joints, etc., (2) by flowing laterally into the edges from saturated shoulders and adjacent earth surfaces, (3) by seeping into the structural section from high groundwater, spring inflows, etc., (4) by being sucked by capillarity from the underlying water table, and (5) by accumulating through condensation of water vapor (water of hydrogenesis) as a result of fluctuations in temperature and other atmospheric conditions. Of all of these sources, surface water is by far the most prevalent and abundant source.

Ideally, if surface waters could be kept out of pavements there would be no need for subsurface drainage except for the control of other sources such as high groundwater, spring inflows, and the like. In spite of the widespread hope that joint repair and seal coat applications will keep surface water out of pavements, the present "state-of-the-art" does not ensure watertight pavements (see Appendix F).

Natural and compacted subgrades at most of the airfields throughout the United States have lower coefficients of permeability than rainfall rates; hence subgrade drainage is slow, and the well-known "bathtub" condition prevails at many locations.

Factual information about all of the above factors has been obtained in the field investigations carried out and described in this report (see Appendixes C, D, E, and F).

There has been a tendency to look upon sand and gravelly sand mixtures as excellent drainage materials, when in reality materials of this kind provide extremely poor pavement drainage. Most of the "standard" base and subbase materials used have relatively low coefficients of permeability, and the drainage rates of these bases (even when provided with edge drains) are quite slow. Consequently, many of the pavements remain filled with water for substantial portions of the year, and water damages are relatively important.

Even well-maintained pavements can accept surprisingly large amounts of surface infiltration, which creates structural flooding when outflow capabilities are less than inflow rates.

Relying upon intuition or judgment for rating the potential inflows and outflows from pavements can be very misleading. In the past, it has resulted in grossly underestimating inflows and greatly overrating the outflow capabilities of the "standard" types of roadbed materials.

The rational engineering approach used in the recently published "Guidelines"[16] makes use of Darcy's law and other seepage principles to estimate all probable inflows into structural sections, and to determine the required transmissibilities of drainage systems. Use of these fundamental principles to develop criteria for evaluating the effectiveness of various kinds of drainage systems is illustrated next.

<u>The Basic Inflow-Outflow Concept in Drainage Analysis</u>. If pavement structural sections are to be kept free of accumulations of excess water, outflow capabilities must always be equal to or greater than all inflows. This can be expressed mathematically in the form of the equation:

$$\Sigma O \geqq \Sigma I \qquad \text{[Eq. 1]}$$

In which, ΣI = all inflow rates
ΣO = total outflow capability.

Equation 1 can be written in the form:

$$O_E + O_S + O_P + O_R + O_D \geqq I_S + I_C + I_T + I_H \qquad \text{[Eq. 2]}$$

In Equation 2, the terms are:

O_E = surface evaporation (usually negligible)
O_S = loss by lateral seepage
O_P = loss by subgrade percolation or drainage
O_R = loss by pumping through cracks in roof
O_D = water removed by subsurface drains

and, I_S = surface infiltration (often major source)
I_C = capillary water from water table (usually minor)
I_T = water transfer from adjacent wet areas or from underlying groundwater or springs
I_H = hydrogenesis water (usually negligible)

Frequently, the terms I_H and I_C are small enough that they can be

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16 *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*, Federal Highway Administration (FHWA) (H. R. Cedergren and Ken O'Brien and Assoc., January, 1973).

neglected. Also, the term I_T, which depends on the subgrade soils, elevation of groundwater, presence of springs, soil profile, and other factors, is often small in relation to I_S. In some cases the terms O_F, O_S, and O_P are quite small. Likewise, O_R is usually quite small, but in some cases may be the major outflow.

In many cases surface infiltration I_S is the major source of water in structural sections. When this is true, the following equation often represents the major factors entering into the balance of inflows vs outflows:

$$O_D \geqq I_S \qquad \text{[Eq. 3]}$$

which says that the rate of flow of water from the drainage system must be equal to or larger (potentially) than surface infiltration.

In order to assure adequate outflow capabilities it is suggested that a factor of safety be used. When this is done, Equation 1 becomes:

$$\Sigma O \geqq C \Sigma I \qquad \text{[Eq. 4]}$$

And, Equation 3 becomes:

$$O_D \geqq C I_S \qquad \text{[Eq. 5]}$$

To provide reasonable allowances for unknown or approximated factors, it is suggested that C should generally be at least 5.

Usually, the significant flows of water into structural sections can be estimated with Darcy's law ($Q = kiA$), in which Q is the inflow quantity, k is the coefficient of permeability of the layer or formation through which the water is flowing, i is the effective hydraulic gradient producing the flow, and A is the cross-sectional area perpendicular to the direction of flow. According to Darcy's law, inflow quantities are proportional to the factors k, i, and A. A simple evaluation of the general magnitudes of these factors aids in understanding the problems of flow of water into structural sections, and of getting water out of structural sections, as outflow rates can also be estimated with Darcy's law using appropriate values for k, i, and A.

Pavements are wide, flat areas with large areas exposed to surface infiltration. When flow is vertically downward, as it is through upper surfaces of pavements, the hydraulic gradient is essentially 100 percent or 1.0, and the entire surface area is a potential source of inflow. So, inflow potentials are relatively large. But, when the flow is <u>horizontal</u>, as through base courses or drainage layers, the amount of area available to drain away the water is quite small, being limited to the thickness of the layer, and the hydraulic gradients are limited to small values. As a consequence, to maintain the proper inflow-outflow balance, base drainage layers need to be considerably more permeable than the surfaces through which water is permitted to enter. In short, road geometrics and the forces of gravity work together to allow large amounts of water to get into structural sections, and poor geometrics and low hydraulic gradients inhibit the flow of water out of structural sections.

Figure 14, which was developed with Darcy's law, shows the discharge capabilities of sloping bases provided with edge drains. The bases are assumed to be 6 inches thick, and flowing full. It is seen, for example, that a 6-inch thick layer of drainage material with a coefficient of permeability of 0.1 cm/sec, on a slope of 0.01, has a discharge capacity of

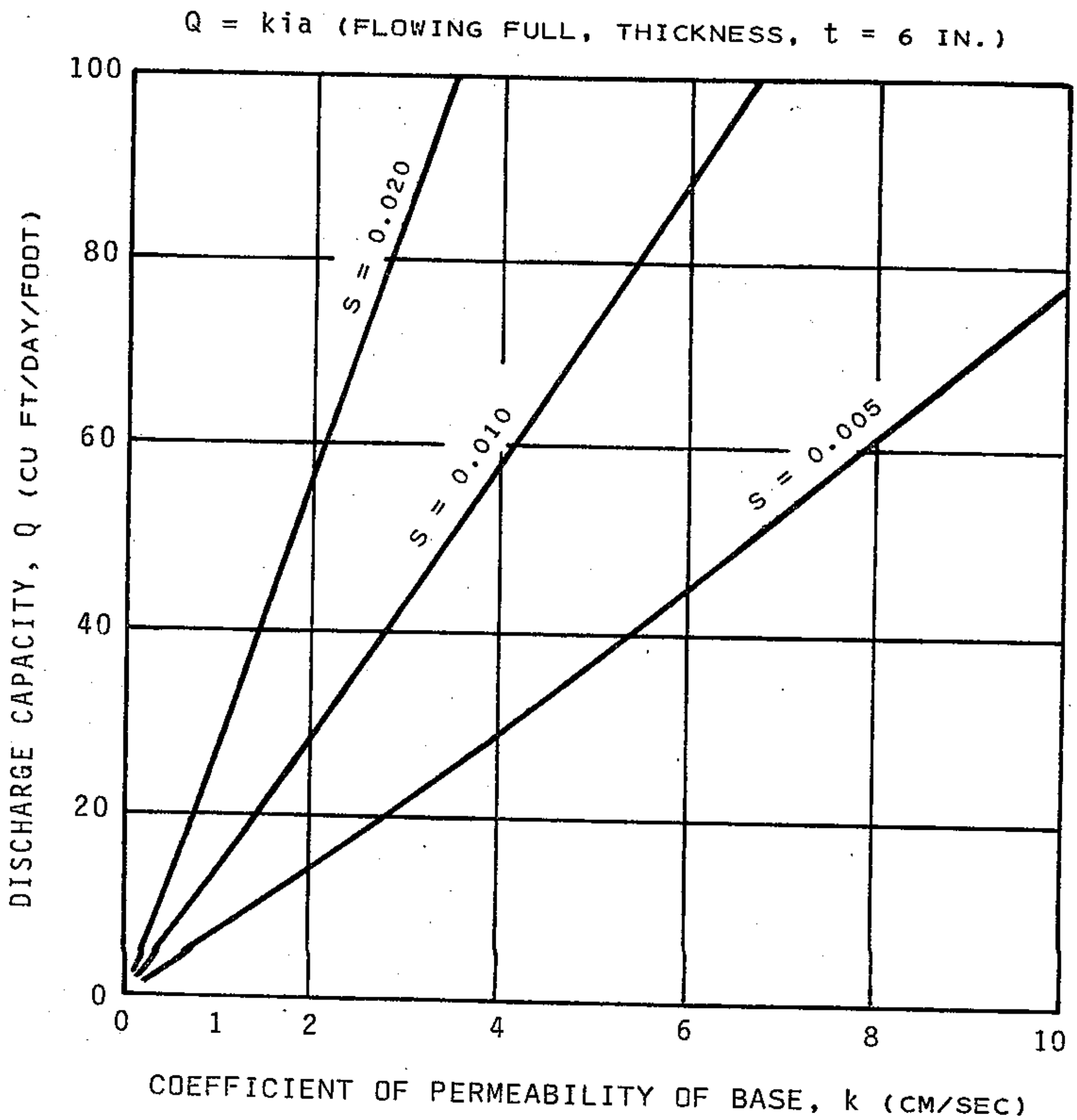


Figure 14. Discharge capabilities of bases with edge drains (thickness = 6 inches).

about 1 cu ft/day/linear foot. In contrast, a 6-inch thick layer of crushed stone with a coefficient of permeability of 8 cm/sec on a slope of 0.01 has a capability for removing over 100 cubic feet per day for each foot of layer.

Charts such as this (Fig. 14) are very useful in establishing the "order of magnitude" of the capabilities of materials used in subsurface drainage systems, and for rating the effectiveness of various classes of materials as drainage aggregates (see also Fig. 25).

Thinking in terms of inflow-outflow balances can aid in developing realistic solutions to drainage problems of many kinds.

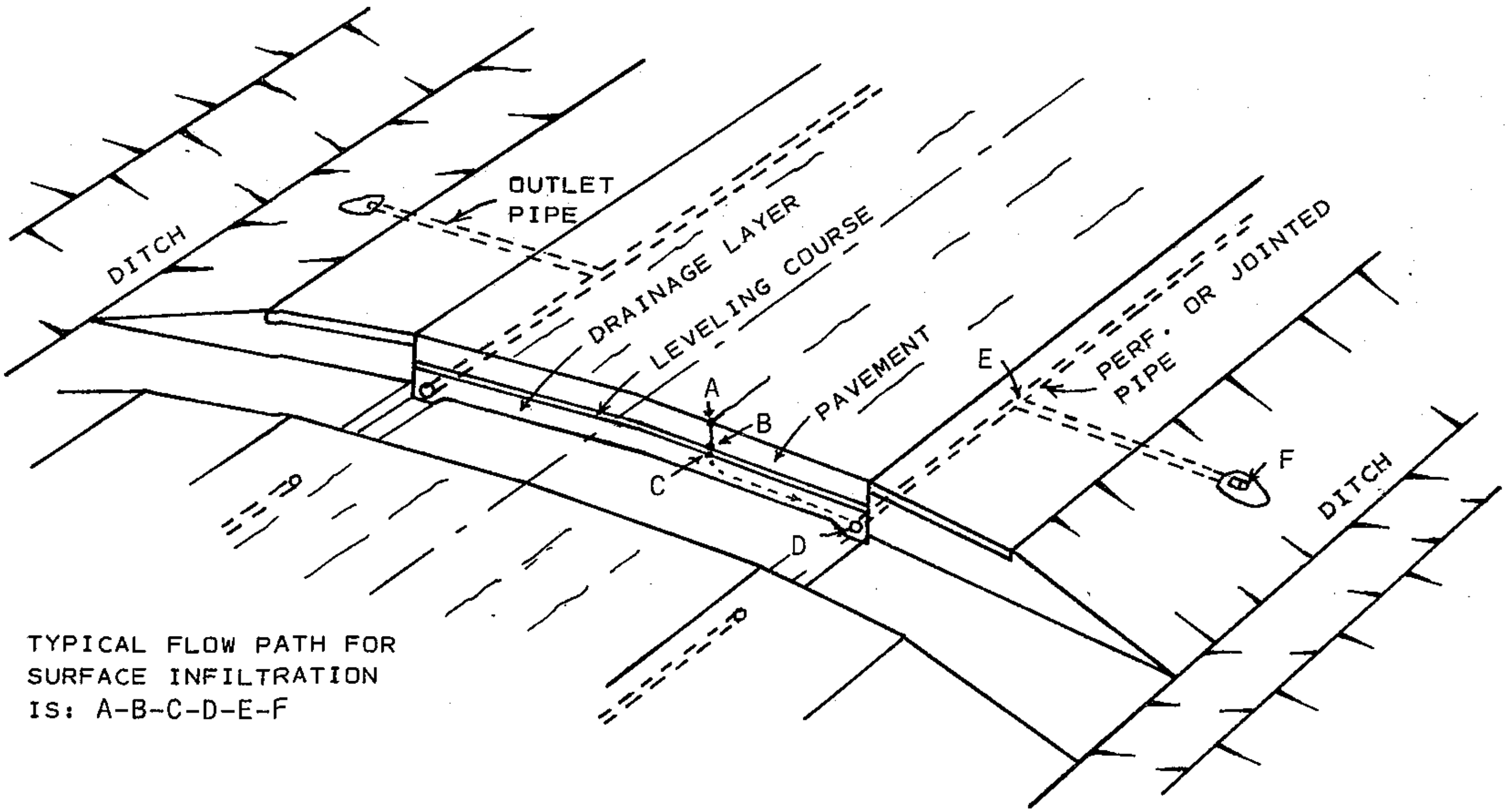
Condition of Continuity as a Drainage Concept. The material presented in preceding paragraphs illustrates the way the basic inflow-outflow concept aids in evaluating subsurface drainage needs of pavements. Outflow capabilities must always exceed inflows, or structural sections can become filled with water to the detriment of the pavements. If accumulations of water within structural sections , and in all parts of drainage systems are to be prevented, outflow capabilities must progressively increase in the direction of flow, from points of entry, through base drainage layers, and through collector pipes and outlet pipes. This principle, which may be called a condition of continuity, provides a useful criterion for verifying the discharge requirements of all component parts of subsurface drainage systems. To illustrate, Fig. 15 shows a section through a pavement-drainage system, with the various flow paths shown by the letters A-B, B-C, C-D, D-E, and E-F. Using the letter Q to designate the seepage capability in any part of the sequence, as determined with Darcy's law or other methods, the following equation must be satisfied if free discharge of water is to be continuously assured:

$$Q_{A-B} \leq Q_{B-C} \leq Q_{C-D} \leq Q_{D-E} \leq Q_{E-F} \qquad \text{[Eq. 6]}$$

When analyzing subsurface drainage systems, Equation 6 is a useful check of the adequacy of all component parts of systems, including the longitudinal pipes and the outlet pipes. Usually it would be desirable to multiply the anticipated inflow Q_{A-B} plus any other expected inflows by a suitable factor of safety, as shown in Equations 4 and 5, before establishing the required properties and dimensions of the drainage elements.

Equation 6 points up the way that maintenance practices can help or hurt the drainage of pavements. Good surface and joint and crack sealing programs, for example, can reduce inflows through the surface, Q_{A-B}, and reduce the load on drainage systems, which is helpful. But poor maintenance practices that allow exit pipes to be crushed or filled with weeds, roots, silt, etc. can cut down on Q_{E-F}, which is definitely harmful.

NOTE: VERTICAL DIMENSIONS OF SECTION ARE EXAGGERATED FOR CLARITY



TYPICAL FLOW PATH FOR SURFACE INFILTRATION IS: A-B-C-D-E-F

Figure 15. Illustration of flow path for condition of continuity in pavement drainage of surface infiltration.

Time to Drain Pavement Structural Sections. Groundwater hydrologists use the term "hydrologic cycle" to describe the occurrence, source, and movement of groundwater in natural earth formations. The occurrence, source, and movement of water within a pavement structural section also has its "hydrologic cycle," although the term has seldom if ever been applied to the rise and fall of water within pavements. Water movements of all kinds follow natural laws and can be studied by using appropriate methods.

For many decades groundwater hydrologists have made extensive use of Darcy's law, often called the "law of flow" in porous media, to analyze groundwater flows and to predict changes due to natural events or man-made influences, such as pumping from wells. And for many decades it has been common practice to monitor changes in groundwater levels by making measurements in wells located throughout a given groundwater system.

Methods for analyzing flow of water into and out of pavement structural sections with Darcy's law are described in this report under "The Basic Inflow-Outflow Concept in Drainage Analysis," and "Condition of Continuity as a Drainage Concept." The fundamental laws of flow as applied to pavements were described in some detail in a recent publication[17]. During the Field Investigation phase of this project, observation wells were installed in pavements at a number of air bases, and the rise and fall of saturation mounds was monitored during and after periods of rainfall (see Appendixes C, D, and E). Those observations indicated that saturation mounds can rise very rapidly during heavy rains, with all of the joints and cracks in pavements usually becoming filled to overflowing within 20 to 30 minutes after the start of a rain. And, after it stops raining, free water often drains quite rapidly out of the upper parts of large cracks and joints in pavements, but remains within the base and lower parts of pavements for extensive periods of time after infiltration stops.

To illustrate the way the fall of saturation and the time to drain can be analyzed, assume that a runway pavement, as shown in Fig. 16, has no significant drainage except by downward seepage into the subgrade. Assume that cracks and joints in the 16-inch thick PCC pavement are equal to 1 percent of the pavement area, and that the effective porosity of the 12-inch base course is 10 percent ($n = 0.1$). In addition, assume an average hydraulic gradient of 0.2 in the subgrade. The general shape of a flow net for subgrade seepage might take the form of that given in Fig. 16, if steady seepage is taking place under the pavement. If the earth shoulders on both sides of the runway are well compacted and properly sloped, surface infiltration in these areas may be small. For these assumptions, the average hydraulic gradient under the pavement would be approximately equal to the slope s of the saturation line on both sides of the runway, which in this example is approximately 0.2.

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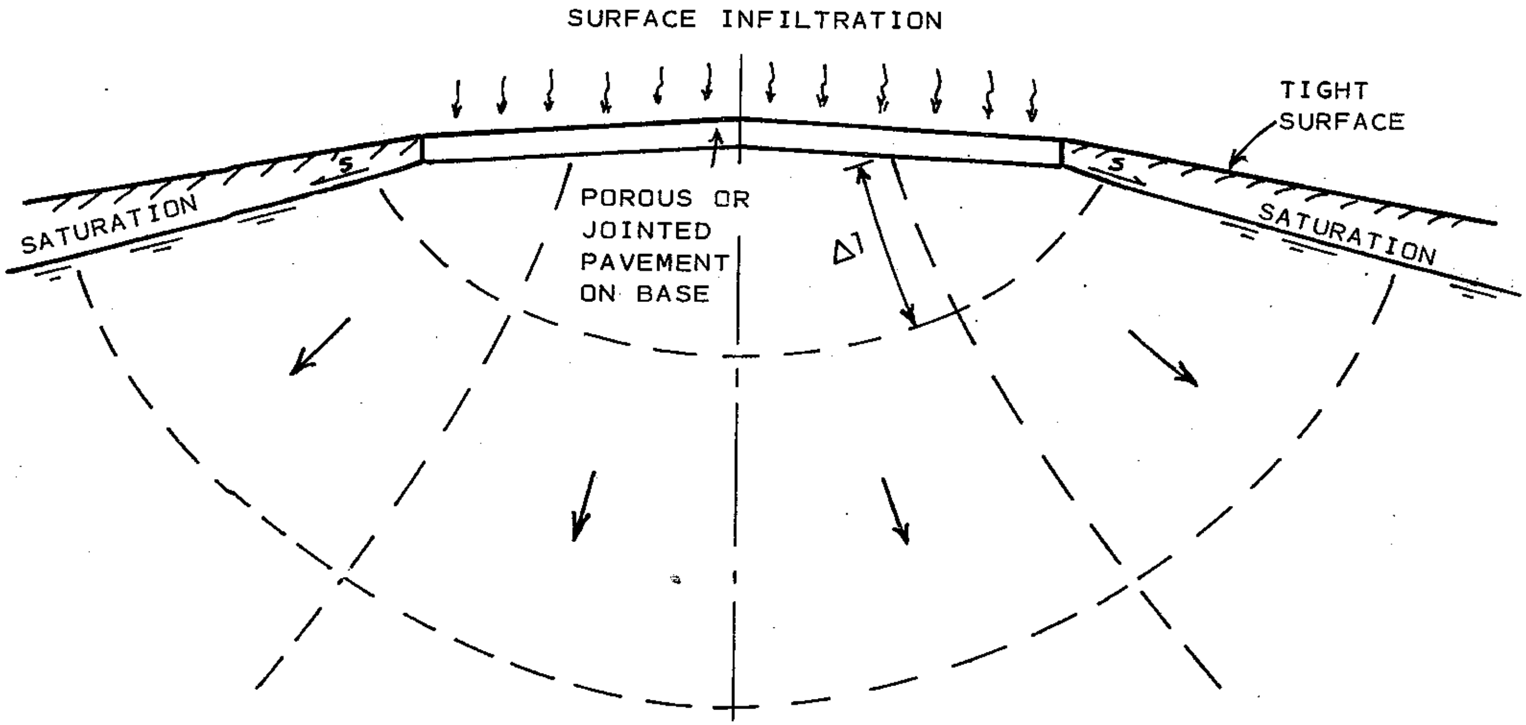
[17] H. R. Cedergren, *Seepage, Drainage, and Flow Nets* (John Wiley & Sons, 1967).



AVERAGE $i = \Delta h / \Delta l$
Δh IS APPROXIMATELY EQUAL TO $s\Delta l$
SO AVERAGE $i = \Delta h/\Delta l = s\Delta l/\Delta l = s$

Figure 16. Flow net for subgrade seepage under runways.

For the conditions represented in Fig. 16, the only outflow of water from the structural section after complete flooding in rainstorms would be $Q_D = O_D = 0.2k$, with k being the effective coefficient of permeability of the subgrade soil. Then, as shown in Fig. 17, rate of fall of saturation and the drainage time depend on the porosity of the layer being drained and the coefficient of permeability of the subgrade. For a coefficient of permeability of 1×10^{-5} cm/sec, approximately 18 days would be needed to completely drain the structural section; for a coefficient of 1×10^{-6} cm/sec the time would be around 180 days. Since many of the compacted subgrades of airfields have permeabilities of less than 1×10^{-5} to 1×10^{-6} cm/sec, the length of the hydrologic cycle and the time of retention of free water can be quite long in many cases. Similar analyses of hydrologic cycles and the time-lag of saturation can be made for any specified pavement-drainage system. Obviously, if pavements are constructed on highly permeable aggregate or other coarse material, fitted with collector pipes and outlet pipes, the saturation build-up and time-lag of drawdown can be virtually zero (see curve for k = 100,000 ft/day or about 35 cm/sec in Fig. 29, Chapter 9).

Summary Comments. By means of Darcy's law, flow nets, and other seepage methods, the rational engineering approach can be used to study seepage within structural sections and to develop criteria for materials for drainage systems that can provide any desired degree of protection from excess water. In preceding paragraphs these principles have been illustrated in relation to three aspects of flow of water through pavement structural sections and out through drains: (1) the basic inflow-outflow concept, (2) condition of continuity, and (3) time to drain pavement structural sections. These fundamental ideas and others also can be used to aid in appreciating the nature and the problems of draining roadbeds and airfields.

In Chapter 9, the effectiveness of subsurface drainage systems will be discussed in terms of (a) cost-effectiveness, and (b) drainage-effectiveness. Drainage effectiveness will be rated, making use of seepage principles as discussed in this report, in terms of several practical criteria: (1) the quantities of infiltration and other inflows that can be removed, (2) the amount of time needed for water to flow completely through a pavement-drainage system, and (3) the time-lag of the rise and fall of saturation mounds in structural sections.

8 SUBSURFACE DRAINAGE SYSTEMS IN USE

General Discussion. Pavement designers generally agree on the need for subsurface drainage systems to handle high water tables, inflows from springs, and the like, but the prevailing philosophy has been that surface water that filters into pavements does not need to be rapidly drained from structural sections.

Current thinking about the ways that water damages to highway and

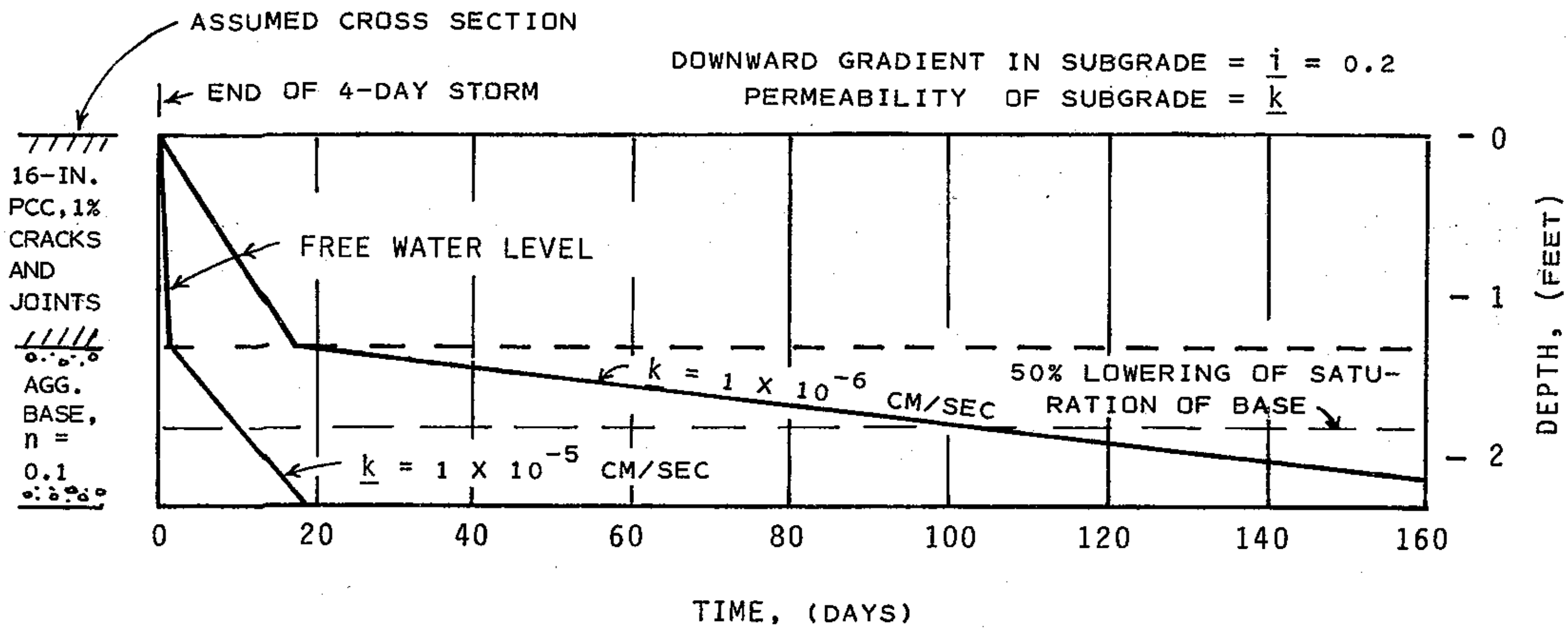


Figure 17. Time-lag of saturation in bases; subgrade drainage only.

airfield pavements can be prevented appears to be well expressed by the following excerpt from the 1971 edition of the Encyclopedia Britannica (Vol. 19, p. 376): "Of the three measures used to keep the roadbed from losing stability, the first is to provide and maintain as impervious a pavement surface as possible. In heavy-duty pavements, a primary purpose of joint sealing and seal coating is to prevent water infiltration. A second measure is to construct the roadbed sufficiently high above the water table--both the normal water table and the temporary fluctuating water table induced by water in the lateral ditches or standing alongside the road. A third measure is the use of roadbed soils that do not attract and hold appreciable water by capillary action. For this reason granular soils are prefered for base courses. Allied to the problem of the detrimental effect of water in the subgrade is the problem of frost heave and the roadbed's subsequent loss of stability during the spring thaw."

Because of their generally good structural properties, widespread availability and general economy, sands and sandy gravel mixtures are widely used as highway and airfield pavement construction materials. Most of these materials have relatively low permeabilities; consequently most pavements are slow draining systems. In many of the locations where airfield pavements have been built, it has been difficult to obtain high quality porous materials.

The primary emphasis in the design of airfield pavements has been on the strengths and stability of the supporting bases and subbases, and most of the airfields have been built without specific subsurface drainage systems. In cold regions, however, longitudinal pipe drains are often placed under outside lower edges of non frost-susceptible bases and subbases. In other cases where severe pumping and surging has occurred, edge drains have sometimes been put in after the problems developed.

Subsurface drainage systems are frequently installed for control over high groundwater, and on occasion for other purposes, as just noted. According to an Army technical manual[18] subsurface drainage facilities may be needed for three purposes: a) Base Drainage, b) Subgrade Drainage, or c) Intercepting Drainage.

Base Drainage is required where frost action occurs in the subgrade beneath the pavement. Subsurface drain pipes are usually laid parallel and adjacent to pavement edges with pervious material connecting the drain with the base. A formula is given in the manual which allows determination of a coefficient of permeability of the base that will assure that such a layer will be 50 percent drained in 10 days after it becomes completely

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[18] *Technical Manual No. TM-820-2,* "Drainage and Erosion Control--Subsurface Drainage Facilities for Airfields," (Headquarters, Department of the Army, August, 1965).

filled with water, and the water supply is then cut off.

Subgrade Drainage is required at locations where seasonal fluctuations of groundwater may rise in the subgrade beneath a paved area to less than a foot below the bottom of the base course. These drains usually consist of either a system of subsurface drain pipes or a system of open ditches. The type, location, depth, and spacing of the drains depend on the soil characteristics and the depth to the groundwater table. Subgrade drains may also drain a base course.

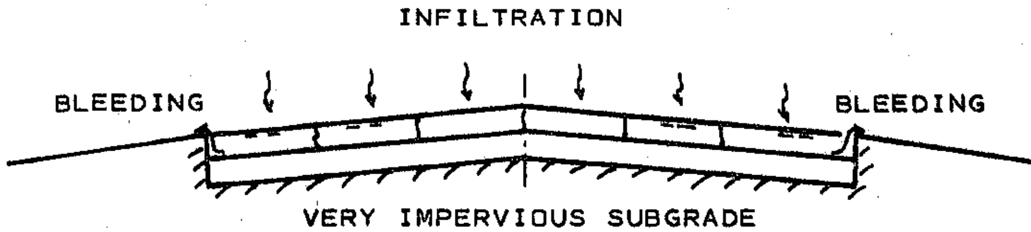
Intercepting Drainage is provided to intercept groundwater flowing in a pervious shallow stratum toward a paved area or into the face of a cut. The type and depth of drain depend on the soil and groundwater conditions.

Many of the older pavements at airfields were forced to carry heavier planes than their capabilities; hence many have been either replaced with heavier designs, or strengthened with heavy overlays after structural problems developed. In many cases where failures occurred they have been attributed to "overloading," or excessive "tracking" of aircraft; however, pavement failures are almost always associated with excess water or free water in structural sections. Studies made for the preparation of this report disclosed a wide variety and range in the drainability of pavements at the airfields studied or visited.

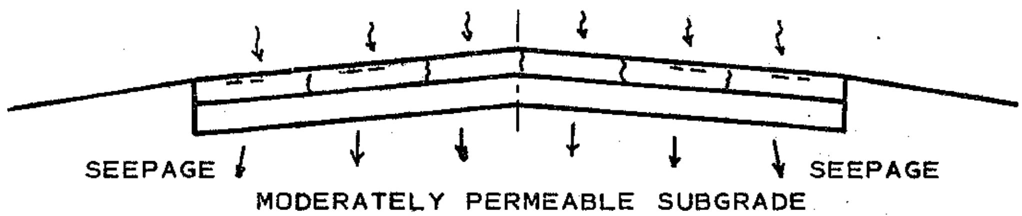
Categorizing Drainage Methods. While there might be a number of ways of categorizing the various methods for draining airfield pavements, the classification selected for this study subdivides the methods according to the direction and manner that water is removed from structural sections. By this approach, the following classification was developed (see Fig. 18): (1) pavements on low permeability subgrades with no designed drainage depend primarily on drainage of the structural section by movement of water out of cracks and joints in the top, or roof drainage; (2) pavements on semi-permeable to highly permeable subgrades and with no designed drainage are drained (in addition to roof drainage) by subgrade drainage; (3) pavements with edge drains in bases or subbases depend primarily on side drainage, or lateral drainage; (4) pavements on trap rock or other highly permeable bases with outlets are drained by downward flow, or by bottom drainage. Many pavements are drained by a combination of the above methods, or by some modification of one or more of these methods.

Following are general descriptions of the drainage methods listed above and illustrated in Fig. 18.

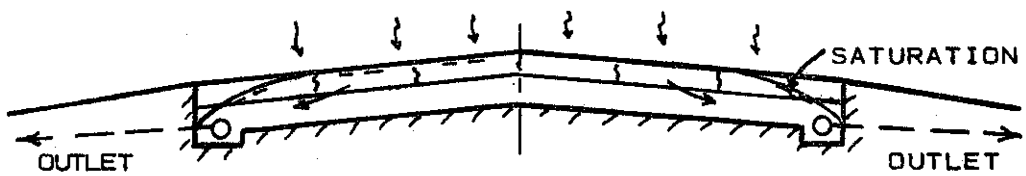
Roof Drainage. Pavements which are constructed on highly impermeable subgrades with no edge drains or bottom drainage layers, often remain partially filled with water for weeks or even months after it stops raining. Gradually, some water slowly soaks downward out of the structural section while some is forcefully ejected or pumped out of cracks and joints by traffic impacts. Water tends to migrate to lower elevations at sag-vertical



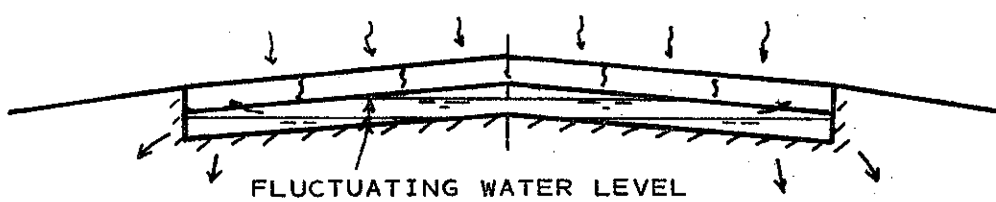
a) Top or <u>roof</u> drainage.



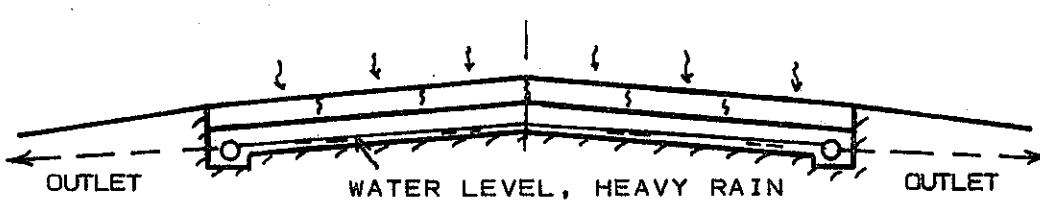
b) Subgrade drainage.



c) Lateral drainage.



d-1) Bottom drainage--no outlet pipes.



d-2) Bottom drainage--with outlet pipes.

Figure 18. Types of subsurface drainage systems.

curves, outside edges, etc., so pavements at higher elevations may become partially drained while those at lower elevations are still filled with water. A large part of the water escapes back through the top or roof of the pavement--some being forced out by thermal expansion, some being forced out under the pressure of passing planes (see diagram a, Fig. 18).

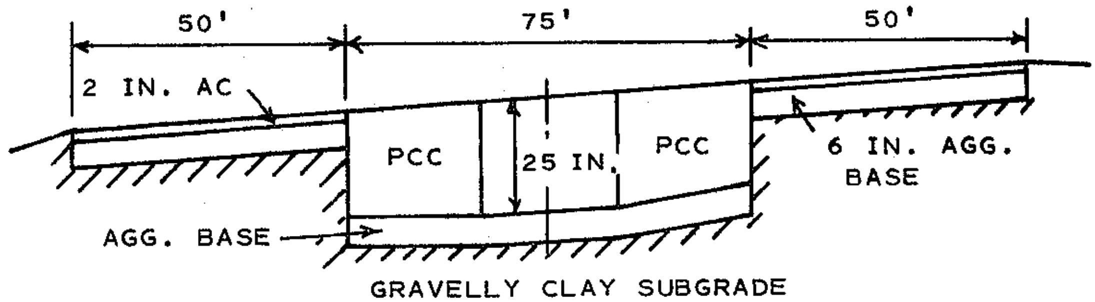
Roof drainage is inherently slow since it is in direct opposition to the forces of gravity. It is the most inefficient kind of drainage. Pavements which depend primarily on top drainage for the removal of excess water may remain in a structurally flooded state nearly 100 percent of the time, greatly accelerating the damages to the pavements. The life-cycle of a pavement with only this kind of drainage may be cut to only a small fraction of that possible with rapid drainage.

Subgrade Drainage. Pavements that are constructed with no drains, but on semi-permeable to highly permeable subgrades, have beneficial downward drainage that is proportional to the in-place coefficients of permeability of the subgrades (see diagram b, Fig. 18). In locations where water tables are deep, the subgrade drainage per square foot of paved area is essentially equal to the vertical permeability of the subgrade. In locations where water tables are shallow, it is proportional to the average hydraulic gradient, and may be as low as a few percent of the subgrade permeability. Illustrative analyses of the capabilities of subgrades to drain pavements are given in Chapter 7, "Fundamental Considerations in Subsurface Drainage" (Figures 16 and 17), and in Chapter 9, "Effectiveness of the Subsurface Drainage Systems" (Figures 24 and 28). Cross sections through some typical airfield pavements which depend primarily on subgrade drainage are given in Fig. 19.

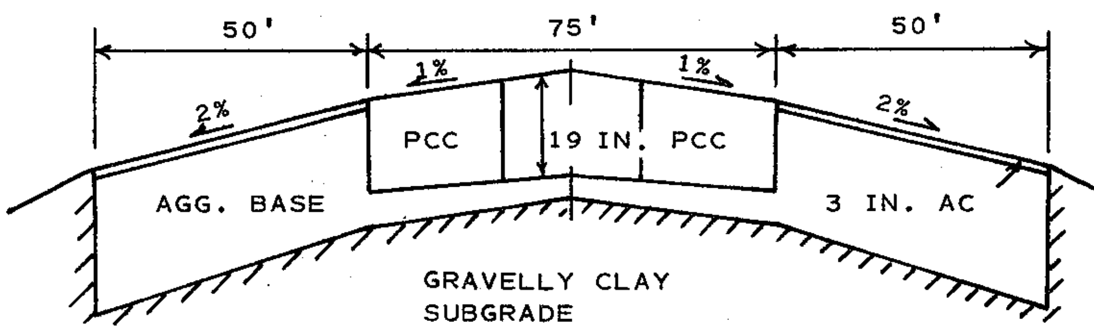
In most parts of the United States, the permeabilities of native and compacted subgrade soils are less than the prevailing rainfall rates, and the well-known "bathtub" condition may exist for many months each year. Figure 20 shows water standing on the base course of a taxiway being reconstructed after the original taxiway failed from poor drainage. Slow subgrade drainage is quite evident, as it hasn't rained for several days after a light shower and considerable water is still standing. An asphalt seal may be helping to retard drainage at this area.

In some cold regions, very permeable dune sands or blow sands provide subgrades for pavements. During warm weather, subgrade drainage in some of these regions is excellent, but if the subgrades become frozen during cold weather, subgrade drainage may be zero during critical periods in the spring thaw.

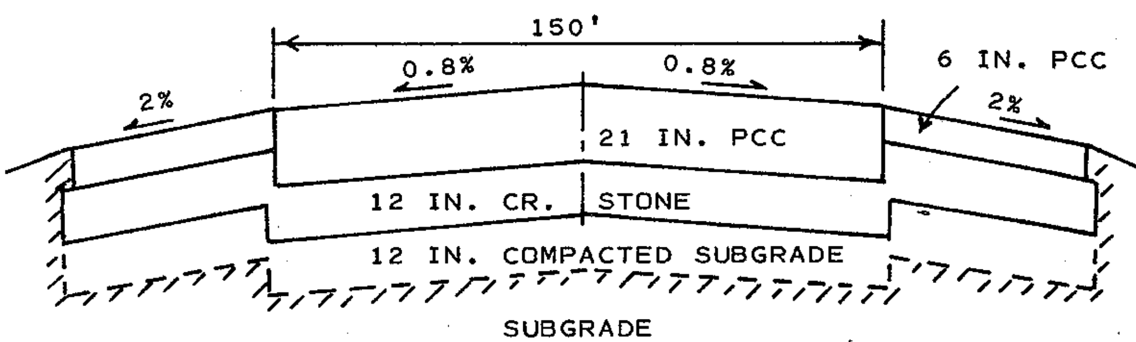
Even among the limited areas of the United States which have highly permeable subgrades that could provide excellent vertical drainage, high water tables often restrict the flow of water out of the structural sections of pavements in these areas. Many of the pavements that depend primarily on subgrade drainage are filled with water substantial amounts of time each year.



a) Taxiway pavement section



b) Taxiway pavement section



c) Stab. pavement section

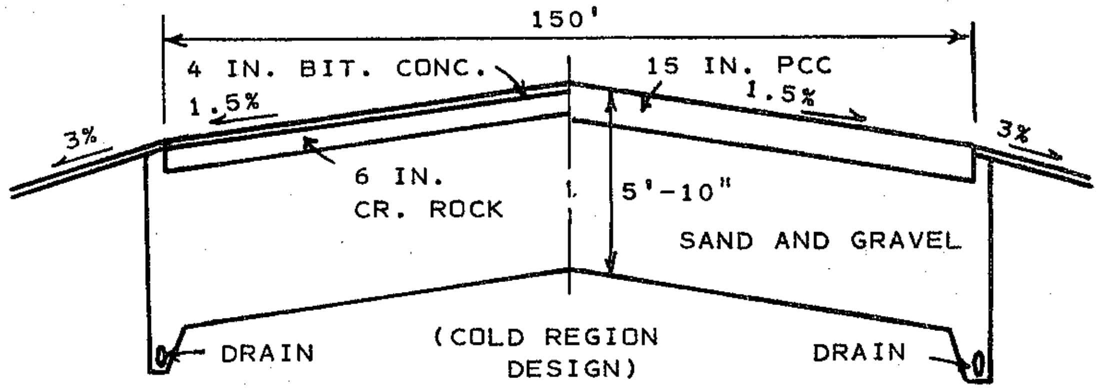
Figure 19. Airfield pavement designs that depend primarily on subgrade drainage.

Figure 20. Photo showing water standing on base course during the reconstruction of a damaged taxiway; several days after a rain. Indicates slow drainage.

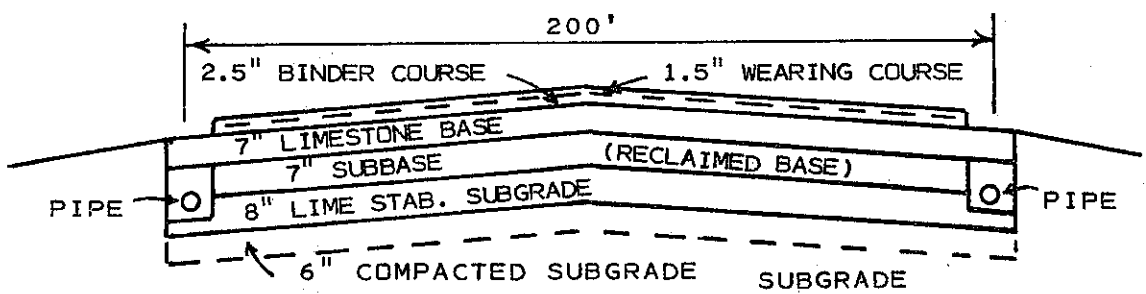
Lateral Drainage. Where pavements on relatively low permeability subgrades are provided with drains under outer edges of bases or subbases, water that enters the structural section must flow in a horizontal direction to get to the drains (see diagram c, Fig. 18, and Fig. 21). Quantities of discnarge from the bases can be estimated with Darcy's law ($Q = kiA$), and are proportional to the in-place permeability k of the base, the lateral hydraulic gradient in the base i, and the thickness or area through which water is flowing, A. Lateral rates of flow in the standard types of bases and subbases in widespread use can be rather sluggish since these materials usually contain relatively high percentages of fines and often have low coefficients of permeability.

Published reports indicate that the normal bases for concrete pavements generally contain from 10 percent to 20 percent of sizes finer than a No. 200 sieve. Some of the materials normally defined as "open-graded" contain four percent or more of material passing a No. 200 sieve. Frequently, bases are stabilized with cement or asphalt (or sealed with asphalt) which increases stability but often lowers permeability. A pavement with edge drains under a stabilized base is illustrated in the bottom diagram in Fig. 21.

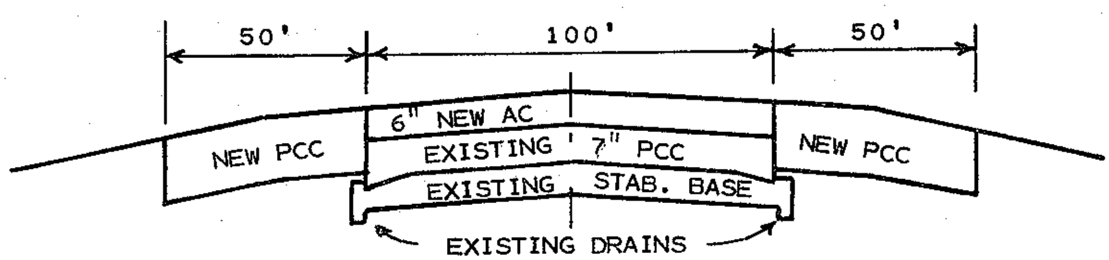
The general level of permeability of the normally used bases and subbases for airfield pavements is given in an Army Corps of Engineers



a) Runway sections.



b) Runway section.



c) Runway section.

Figure 21. Airfield pavements with underdrains for lateral drainage.

Engineering Manual[19] from which the information in Table 4 was obtained. That manual says crushed rock or slag without any fines usually has permeabilities greater than 0.5 cm/sec (1440 ft/day). A table in that manual

Table 4

Permeability versus Fines Content of Base Materials

Percent by Weight Passing a No. 200 Sieve	Coefficient of Permeability for Remolded Samples (cm/sec)	(ft/min)
3	0.5×10^{-1}	10^{-1}
5	0.5×10^{-2}	10^{-2}
10	0.5×10^{-3}	10^{-3}
15	0.5×10^{-4}	10^{-4}
25	0.5×10^{-5}	10^{-5}

indicates general levels of permeability for a wide range of materials, such as the following:

Remolded clean gravels:	1 to 100 cm/sec
Clean sand and clean sandy gravel:	1×10^{-3} to 1 cm/sec.

A Federal Aviation Administration Advisory Circular[20] points out that base course materials meeting FAA Construction Specifications P-154, P-208, or P-209, would have sufficient fines to reduce permeability coefficients to the range of 10^{-1} to 10^{-4} cm/second. It says, "Pavement courses that have been adequately stabilized with cement or bitumen are impermeable, therefore, a pavement edge drain system would be necessary." That circular also says, "The control of moisture under pavement is the principle reason for subsurface drainage along the pavement edges." It indicates that free water may collect below the pavement under several conditions, including (1) a water table that rises into the base or subbase during an exceptionally wet season, (2) a water table high enough to supply capillary water

19 *Technical Manual No. 5-820-2*, "Drainage and Erosion Control--Subsurface Drainage Facilities for Airfields"(Headquarters, Department of the Army, August, 1965).

20 *Airport Drainage*, Advisory Circular 150/5320-5B, Department of Transportation (Federal Aviation Administration, July, 1970).

to the top of the subgrade, or (3) thawing frost layers releasing free water.

A comprehensive investigation by Strohm et al[21] showed that normal base course materials can have exceedingly low coefficients of permeability and almost zero porosity when thoroughly compacted. The drainage provided by such bases is virtually nil, and water that enters structural sections with bases of this kind drains out very slowly. When water is retained in structural sections because of drainage rates that are slower than inflow, each pass of a heavy plane may force water up through cracks and joints in the pavement surface, where some of it dries by evaporation. Such bleeding or surging has been observed at many military and non-military airfields, where the bases and subbases have contained as little as one or two percent of material passing a No. 200 sieve.

Indications of the rates of drainage that can be obtained with drains placed along the outside, lower edges of bases are given by illustrative analyses in Chapter 7, "Fundamental Considerations in Subsurface Drainage" (Fig. 14), and in Chapter 9, "Effectiveness of the Subsurface Drainage Systems" (Figures 25 and 29). A normal type of base course with a permeability coefficient of 0.002 cm/sec (6 ft/day) can remove an overall infiltration rate of only 0.00005 inch/hour entering into a half-width of a 300-ft wide runway (Fig. 25). In contrast, a 6-inch thick base of highly permeable open-graded rock (k = 20 cm/sec) can remove approximately 0.5 inch/hour from the same width pavement (Fig. 25). Solutions such as those referred to here can aid in understanding the nature of the problem of draining wide, flat pavements.

Mr. C. C. Calhoun, Jr.[22] describes an investigation of bleeding pavements. A pavement base course contained 16 to 26 percent of material finer than a No. 200 sieve, and had been so thoroughly compacted that internal parts of the base were literally "bone dry" while its upper side in contact with a PCC pavement was extremely wet and muddy to a depth of 1/4 to 1/2 inch. The study concluded that edge drains would be ineffective in draining the pavement structural section (a cross section through a runway at this airfield is included in Fig. 21).

A criterion suggested by Casagrande and Shannon[23] would ensure that

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[21] W. E. Strohm, E. H. Nettles, and C. C. Calhoun, Jr., "Study of Drainage Characteristics of Base Course Materials," *Highway Research Record No. 203* (Highway Research Board, 1967).

[22] C. C. Calhoun, Jr., *Miscellaneous Paper S-69-26* (Waterways Experiment Station, April, 1969).

[23] A. Casagrande and W. L. Shannon, "Base Course Drainage for Airport Pavements," *Proceedings of the ASCE*, Vol. 77, Separate No. 75 (June, 1951); Also, *Transactions of the ASCE*, Vol. 117 (1952) pp. 792-820.

bases for airfield pavements would have sufficient permeability to provide 50 percent drainage following complete saturation, within 10 days (see "Time-Lag of Fall of Saturation in Structural Sections," in Chapter 9). If this criterion were used, it would eliminate the use of base materials containing high percentages of fines. Inquiries that were made as part of the study for this report indicated that this criterion has been used to only a limited degree.

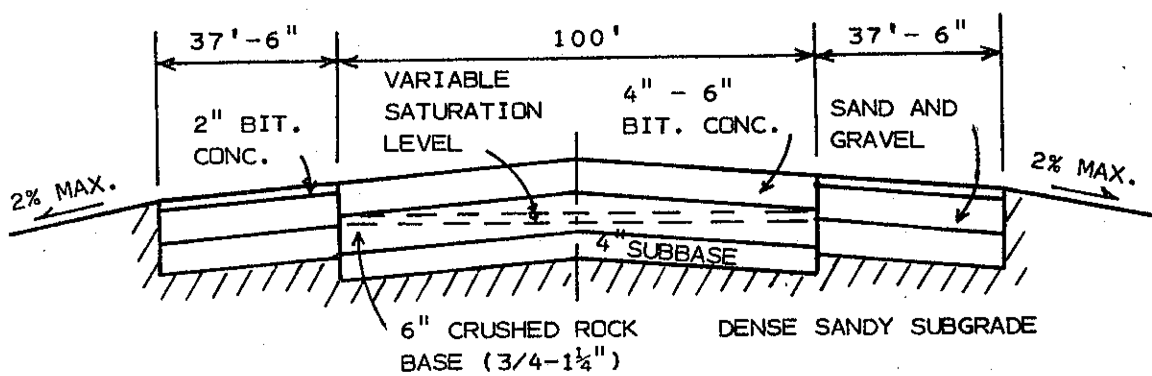
As indicated by analyses in Chapter 9, "Effectiveness of the Subsurface Drainage Systems," if bases are to have sufficient permeability to give a high level of protection against the harmful effects of excess water, their coefficients of permeability need to be in the range of 3 to 30 cm/sec. This requires the use of clean, coarse pea gravel or crushed stone or gravel in the range of 1/4 inch material up to 1 inch material.

It has been known for many years that placement conditions can have a major influence on the permeabilities of granular materials, causing field permeabilities to be either larger or smaller than laboratory permeabilities of the same materials. In a series of tests that were made by the Cold Regions Research Laboratory (CRREL), and described with a letter from Mr. E. F. Lobacz to Dr. E. Barenberg on 10 Nov. 1972, field permeability tests on base and filter materials gave coefficients of permeability 10 to 15 times greater than were obtained from laboratory tests. The differences were attributed to segregation and lamination of the base course materials during construction. Such effects are believed to be responsible for higher than expected permeabilities of a drainage course under pavements at one of the field investigation sites (see Appendix F).

Cross sections through some airfield pavements that had edge drains were given in Fig. 21. The upper diagram is a runway section with a very thick, non-frost susceptible base which has pipe drains along the outer edges. Because of the thickness of the base and the limitations imposed on the amount of fines in non-frost susceptible bases, this section is probably quite well drained. The pavements in the middle and lower diagrams in Fig 21 are probably not very rapidly drained because of the lower permeabilities of the bases.

Bottom Drainage. The most efficient way to drain water out of pavements is to allow free gravity flow downward out of the primary pavement layers and out of the interfaces between pavements and their bases (see diagrams d-1 and d-2, Fig. 18). Downward flow (into a highly permeable base drainage layer) has the greatest efficiency because of several primary factors: (1) the forces of gravity are working in the direction of flow, producing hydraulic gradients in the order of 100 percent; (2) the seepage distances are the minimum possible, as they are equal to the thicknesses of the layers being drained; (3) the cross-sectional areas through which seepage is taking place are the maximum possible (the plan areas of the layers being drained). In other words, <u>downward drainage makes the maximum possible use of all of the key factors affecting the rate of drainage</u>. By Darcy's law, the potential downward rate of flow from a structural layer into a freely drained bottom drainage layer is Q = kiA = k(1.0)A = kA. And, per square foot of pavement area, q = k. This high level of drainage is seldom achieved in the normally used structural sections.

When drainage layers with very high levels of permeability are placed under the full widths of pavements as in diagram d-2, Fig. 18, accumulations of excess water within pavements and at interfaces between pavements and bases are held to a minimum. To assure the fullest benefits from these layers, they must have free gravity drainage through suitable collector pipes and outlet pipes placed at lower edges, so they seldom if ever can become filled with water. If pipes or other positive outlets are not provided, the water level in these bases will quickly equalize by flow of water from high pavement areas to low pavement areas (as shown in diagram d-1, Fig. 18, and in Fig. 22, which shows an airfield pavement constructed on coarse trap rock, but with no pipe drains). If inflows continue to exceed outflows by top drainage or by subgrade drainage, bases may become



Heavy Duty Bituminous Concrete Taxiway

Figure 22. Airfield pavement with partial bottom drainage.

completely filled, and then they will provide no protection at all to the overlying pavements. But, as long as the saturation level remains even an inch or two below the top of an open-graded base, and free communication with the outside atmosphere is permitted, excess pore pressures cannot build up and the damages from excess water will be minimized.

When pipes are provided as shown in diagram d-2, Fig. 18, with free gravity flow out of the pipes, open-graded bases can provide the best possible drainage of pavements. The capabilities of open-graded bases for removing water from structural sections are illustrated by Fig. 25 under "Rates of Surface Infiltration and Other Inflows that Can Be Removed."

Base courses of "trap rock," crushed limestone, crushed gravel, and other materials of comparable properties are sometimes used for both highways and airfields. Evidently, little thought is ordinarily given to the possibility that such bases (often extremely permeable) can serve as distinct drainage layers if outlets are provided. When they are used without drainage outlets they usually serve as equalizing reservoirs. Water flows very rapidly in these layers to low elevations along alignments and to outer edges, often benefiting the portions of pavements that are at higher elevations, but building up damaging artesian pressures under portions of pavements at lower elevations (diagram d-1, Fig. 18, and Fig. 22). Under these conditions, the paved areas at crowns may be well drained much of the time while the lower areas develop problems from excess water. If suitable collector pipes and outlet pipes were installed in these highly permeable bases, and water could rapidly drain out by gravity flow, excellent drainage could be obtained.

Subsurface drainage systems of the kind shown in diagram d-2, Fig. 18, can provide the highest possible level of protection to pavements from excess water. This type of system was recommended in a new report[24] issued by the Federal Highway Administration (FHWA) in January, 1973, for the design of subsurface drainage systems for highway pavement structural sections.

<u>Summary Comments</u>. To provide a basis for evaluating the effectiveness of drainage systems in use and potential improved methods, subsurface drainage systems were categorized on the basis of direction and manner that water is removed from structural sections. By this approach, the following classifications were developed: (1) roof drainage, (2) subgrade drainage, (3) lateral drainage, and (4) bottom drainage.

Charts and curves that are given in Chapter 7 and Chapter 9 of this report provide several criteria for evaluating the effectiveness of the various kinds of drainage systems, as categorized here. It is shown that extremely wide variations in effectiveness can be expected, depending on the kind of system used, and the permeabilities of the materials controlling the drainage. Pavements with no underdrains of any kind, constructed on impermeable subgrades are the most poorly drained; those on impermeable subgrades and having edge drains may be somewhat better, but often are still very slowly drained; those on very permeable subgrades may be very well drained except during any periods when the subgrade is frozen; those with full-width, very permeable open-graded bases with collector pipes and outlet pipes are the very best.

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[24] *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*, Federal Highway Administration (FHWA)(H. R. Cedergren and Ken O'Brien & Assoc., January, 1973).

Most of the airfields investigated in this study depend primarily on roof drainage and subgrade drainage, although a number had been provided with some pipe drains for lateral drainage, either during original construction or after problems with water had developed. Some had been provided with wells to try to correct localized conditions that appeared adaptable to this kind of treatment. In general, the airfields investigated had drainage capabilities that ranged from "poor" to "fairly good," as far as surface drainage is concerned. A fully adequate subsurface drainage system wad found in only a few cases. One 10,000-ft runway and taxiway system that visited had been reconstructed in 1969 on a very comprehensive subsurface drainage system which contained over 16 miles of pipe drains[25] (see Fig 23). This is the only major airfield pavement system called to our attention with such a comprehensive subsurface drainage system. As noted elsewhere in this report, it added less than 5 percent to the total cost of the pavement reconstruction. The full benefits of the rapid drainage provided by this system will not be known for a number of years, although it seems likely that the slight added costs have already been repaid.

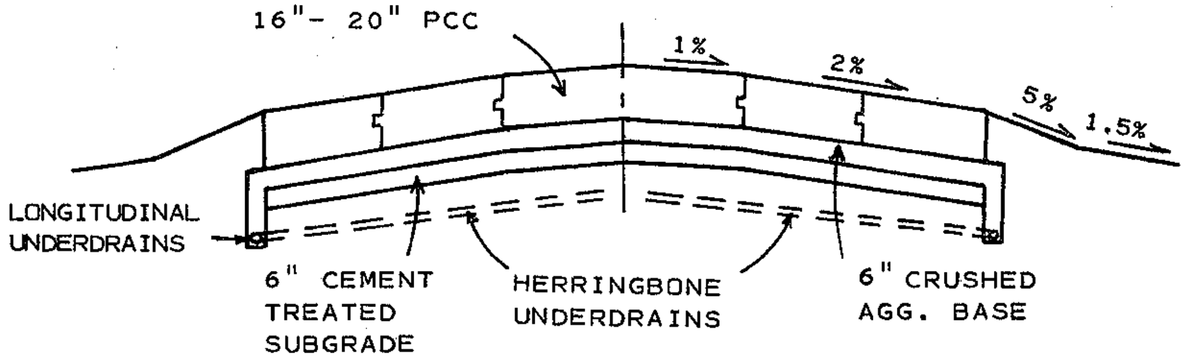

Figure 23. Airfield pavement with combined bottom drainage and lateral drainage.

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[25] Robert W. Richards, "Atlanta's Instant Runway," *Transportation Engineering Journal, Proceedings of the ASCE* (August, 1971), pp. 491-500.

9 EFFECTIVENESS OF THE SUBSURFACE DRAINAGE SYSTEMS

Basic Considerations. The true effectiveness of any construction feature can be measured in the amount of trouble-free service provided per dollar outlay over the life of the feature. With respect to pavements with or without subsurface drainage systems, their total effectiveness can be measured in terms of the original costs plus all important upkeep and repair costs, amortized over the useful life of the pavements. Original cost alone is not very meaningful if the actual service life of the pavements is not taken into consideration. The direct benefits of pavement-drainage systems are the amounts of serviceable pavement areas provided, and the number of load applications that can be handled over the life of the pavement. Cost-effectiveness studies are presented here on the basis of (1) annual costs per square yard of pavements provided, and (2) pavement costs per cycle of B-52's over the useful life of the pavements. Routine maintenance costs are assumed to be about the same for both the drained and undrained pavement structural sections, and are neglected in the comparison of undrained and drained pavements.

In carrying out the work required under this contract, only limited maintenance cost information could be obtained about the pavements at the airfields included in the studies, so limited factual data were available to compare the costs incurred because of a lack of drainage. Two very noteworthy cases were found, however, which appear to be very significant examples: (1) a major airfield that had required runway repairs totalling nearly $3,000,000 to counteract extensive "D" cracking that the engineers felt was at least partially caused by excess water in the pavements, and (2) a major metropolitan airport where a primary runway had failed from excess water and heavy traffic, and the designers of the new runway had incorporated a "comprehensive" underdrainage system containing a base drainage layer and 16 miles of pipe drains, which increased the total cost by less than 5 percent. The added repair costs in the first example are perhaps 50 percent or more of the original costs of the pavements, and the problems have not been totally corrected. By comparison, the extra costs for the unusually comprehensive subsurface drainage system in the second example are quite minimal. In areas where "D" cracking is a serious problem, good quality aggregates are often difficult and expensive to obtain. Application of the solution method utilized in Example 2 would be perhaps more expensive if applied to the Example 1 airfield. But by increasing the initial cost of the pavements in Example 2 by 5% it is possible that further extensive costs, such as those occurring in Example 1, may not be incurred. If, as suggested by the "D" cracking study of Verbeck et al[26], extensive exposure to free water is necessary for "D" cracking

[26] George Verbeck, Paul Klieger, David Stark, and Wilmer Teske, *Interim Report on D-Cracking of Concrete Pavements in Ohio*, Agreement No. 1910, Ohio Department of Highways with Portland Cement Association (PCA), Research and Development Laboratories, Skokie, Illinois (March, 1972).

to become a problem when low quality aggregates must be used, it seems to the author that the extra costs for high quality drainage aggregates might be more than offset by reduced "D" cracking damage and repair costs, F.O.D. damage, and "down time" for the users of a facility.

While the direct way to evaluate the effectiveness of subsurface drainage systems for pavements is on the basis of cost-effectiveness, as noted above, another way is on the basis of drainage-effectiveness, as will be discussed later in this report. Several practical criteria are used in that method of evaluation of the effectiveness of drainage systems.

Cost-Effectiveness of Subsurface Drainage Systems.

1. *Basic Data Used.* This section presents procedures that can be used for comparing the cost-effectiveness of well drained pavements with normal undrained pavements. It makes use of original costs for an actual runway and the known repair and overlay costs that were attributable in a large measure to slow drainage. The comparisons are made on the basis of cost per square yard of pavement per year of service, and also on the equivalent cost per cycle of operation of B-52's.

The selected runway was built in stages, from 1947 through 1959. A median starting point for the study is taken as 1950. Although the total length of the 300-ft wide runway is 12,600 feet, the 300-ft x 11,000-ft portion of heavy-duty PCC pavement was selected for the study. Other extensions were made several years after the 11,000-ft portion had been finished. Approximately 367,000 sq yds of pavement are included in the portion used in the study.

The 11,000-ft portion is 21-in. thick PCC with 3-in. x 3-in. welded fabric reinforcing, and is on a base course of variable thickness. A 12 inch base thickness was assumed for cost estimating.

The following major costs have been required because of severe "D" cracking, spalling and blow-ups:

1964: Sawing, chipping, and epoxy repairing for a cost of $1,260,000 (For 367,000 sq yds, this is $3.44 per sq yd).

1971: 4-in. thick AC overlay for a cost of $1,450,000 (For 367,000 sq yds, this is $3.95/sq yd).

On the basis that the 1964 repairs extended the useful life to 1971 (21 year life at that time) and that the 1971 repairs will extend the useful life to 1975 before other major repairs will be required (25 year life), the following cost comparisons are made. These comparisons allow for inflation that has occurred, and all costs are compared on a present worth basis in the year 1950. For the purpose of calculating the 1950 present worth of expenditures occurring in later years, a discount rate of 6 per cent is used.

2. *Annual costs of Undrained Design.* Use the following for 1950 prices: concrete at $7.00/cu yd + $3.00/bbl for cement for $10.75/cu yd for a 5 sack mix. Aggregate base (12 inches thick) at $3.00/cu yd. Wire fabric at $0.50 per sq yd. Then the cost for 21-in. PCC = $10.75(21/36) = $6.30 per sq yd for concrete, for a total unit cost of $6.30 + $0.50 + $1.00 = $7.80 per sq yd, and a total cost of $7.80 x 367,000 = $2,860,000.

The amounts expended on this pavement now become:

Original cost (1950)		= $7.80/sq yd
1950 present worth of 1964 repairs ($1,260,000 for 367,000 sq yds)		= $1.52/sq yd
	SUBTOTAL	$9.32/sq yd
1950 present worth of 1971 repairs ($1,450,000 for 367,000 sq yds)		$1.16/sq yd
	TOTAL	$10.48/sq yd

COST/SQ YD

Up to just prior to the 1971 repairs (21 years), the annual cost is $9.32/21 = $0.44/sq yd/year.

Up to 1975 (25 years), the annual cost will be $10.48/25 = $0.42/sq yd per year.

COST/CYCLE OF B-52's

If 20,000 cycles of operation would occur in 20 years, the amount would be 21,000 in 21 years, and 25,000 in 25 years for a constant rate of application. Then, the cost/cycle of operation can be estimated as follows:

Total discounted cost to just prior to the 1971 repairs = $2,860,000 + $556,900 = $3,416,900, and the cost/cycle = $3,416,900/21,000 = $163/cycle.

Total discounted cost to just prior to 1975 repairs = $3,416,900 + $426,500 = $3,843,400, and the cost/cycle = $3,843,400/25,000 = $154/cycle.

3. *Annual Costs of Drained Design.* Use the same unit prices for PCC and aggregate base as for the undrained design, but allow the following for an open-graded rock drainage layer (substituted for part of the aggregate base): 6 inch layer at $4.50/cu yd, for an additional cost of ($4.50 - $3.00) = $1.50/cu yd, for $1.50/6 = $0.25/sq yd. 20,000 lin. ft of pipe drains at $3.50/ft will add about $70,000 to the total cost, or $70,000/

367,000 = $0.20/sq yd, for a total extra unit cost of $0.25 + $0.20 = $0.45/sq yd. The total unit cost is $7.80 + $0.45 = $8.25/sq yd.

It is considered possible that rapid drainage at this location might virtually eliminate "D" cracking and blow-ups; however, some spalling damage might need repairing. It appears reasonable to assume that the drained section would probably have eliminated at least 80 percent of the major repairs that were needed, as a recent report by the PCA[27] indicates that there is a definite relation between the length of exposure to free water and the extent of development of "D" cracking. On the basis that good drainage would eliminate 80 percent of the "D" cracking repair costs, the costs for the drained design over the period of the study would be as estimated here:

Original cost (1950 prices)		
(Total cost = $8.25 x 367,000 = $3,030,000)		= $8.25/sq yd
1950 present worth of 1964 repairs (0.20 x $556,900 = $111,400)		= 0.30/sq yd
	SUBTOTAL	$8.55/sq yd
1950 present worth of 1971 repairs (0.20 x $426,500 = $85,300)		= 0.23/sq yd
COST/SQ YD	TOTAL	$8.78/sq yd

Up to just prior to the 1971 repairs (21 year life) the annual cost would be $8.55/21 = $0.41/sq yd/year. This is ($0.41/$0.44)(100) = 93 per cent of the average cost of the conventional pavement based on 1950 present worth of costs.

Up to just prior to the anticipated 1975 repairs (25 year life), the average annual cost would be $8.78/25 = $0.35/sq yd/year. This is ($0.35/$0.42)(100) = 83 percent of the cost of the standard pavement based on 1950 present worth of costs.

COST/CYCLE OF B-52's

If 21,000 cycles of operation would occur in 21 years and 25,000 in

[27] George Verbeck, Paul Klieger, David Stark, and Wilmer Teske, *Interim Report on D-Cracking of Concrete Pavements in Ohio*, Ohio Department of Highways with Portland Cement Association (PCA), Agreement No. 1910, Research and Development Laboratories, Skokie, Illinois (March, 1972).

25 years, as in the previous example, the cost/cycle of operation could be estimated as follows:

Total cost just prior to the 1971 repairs = $3,030,000 + $111,400 = $3,141,400 and the cost/cycle would be $3,141,400/21,000 = $150/cycle. This is ($150/$163)(100) = 93 percent of the cost of the conventional pavement based on 1950 present worth of costs. It is $13 less cost per cycle.

Total cost to just prior to 1975 repairs = $3,141,400 + $85,300 = $3,226,700, for a cost/cycle of $3,226,700/25,000 = $129/cycle. This is $25 less cost per cycle than that experienced using the undrained section or ($129/$154)(100) = 83 percent of the conventional pavement based on 1950 present worth of costs.

It should be noted that the above comparisons do not include any allowances for losses to users of the facility due to down time for repairs, damage to jet aircraft from FOD, and other related costs of unserviceable pavements, which can be expected to be larger for the conventional pavement than for the well drained pavement. It is also pointed out that the routine annual maintenance costs have been neglected in these computations. It is thought that these expenses would be less if a well drained pavement section is used.

Drainage-Effectiveness of Subsurface Drainage Systems. If the damages that can occur with free water in structural sections are appreciably greater than while they are freely drained, it becomes important to set criteria to assure that water is removed quite rapidly, as cost-effectiveness is dependent on drainage-effectiveness. Very basic and practical methods for analyzing seepage in subsurface drainage systems are contained in Army Design Manuals such as *TM 5-820-2*, "Drainage and Erosion Control--Subsurface Drainage Facilities for Airfields," Department of the Army, August, 1965, and in other publications. The present discussion is considered supplementary to other sources of information that have been published by the Army and other agencies designing airfield pavements.

When subsurface drainage systems are designed as rapidly draining systems, a high level of protection against all forms and occurrences of water within pavements will usually be obtained. But, if drainage capabilities are low, several deficiencies will show up. The following three aspects of water in structural sections are considered useful in judging the adequacy and effectiveness of subsurface drainage systems.

1. Rates of surface infiltration and other inflows that can be removed by the systems.

2. The amount of time needed for water to pass completely through a subsurface drainage system (particularly important in cold regions), and

3. The time required for saturation mounds to fall after inflows stop.

These three aspects of drainage are discussed in succeeding paragraphs.

Rates of Surface Infiltration and Other Inflows that Can be Removed. If no drains of any kind are provided, some water will bleed out at lower edges of the pavement by roof drainage, but sometimes the only significant drainage is into the subgrade. If the water table under a pavement is quite deep, say 40 or 50 feet or more, downward seepage per square foot of paved area will often be in the range of 25 to 100 percent of the coefficient of permeability of the subgrade soil. But, if the water table is shallow, the effective hydraulic gradient is reduced, and since the unit outflow = ki, the rate of drainage into the subgrade may be as low as 2 or 3 percent of the effective permeability. In many areas of the United States, compacted subgrades have coefficients of permeabilities less than normal rainfall rates that occur frequently each year. In such areas, drainage into the subgrade may be quite slow, and rough approximations of rates will suffice in seepage analyses. In Chapter 7, a flow net for subgrade seepage for a hypothetical pavement was given (Fig. 16), and some calculations of drainage into the subgrade were given in a chart (Fig. 17). To further illustrate the potential for subgrade drainage, Fig. 24 was prepared. It gives rates of drainage into subgrades for average downward hydraulic gradients of 0.1, 0.2, 0.5, and 1.0. By examining this chart, it is seen that if subgrade drainage is to be significant in relation to normal rainfall rates in many parts of the United States, compacted subgrades must have coefficients of permeability (with fairly low water tables) in the order of 0.01 cm/sec (20 or 30 ft/day), or greater. Compacted subgrades having much lower coefficients of permeability can be expected to give only limited pavement drainage. Figure 24 is illustrative, and in many cases where water tables are quite shallow, subgrade drainage will be much less than the rates given in this chart.

When base courses or drainage layers under pavements are provided with edge drains and outlets to provide gravity discharge of water from the bases, flow is essentially in a horizontal direction in the bases. Analyzing this condition with Darcy's law, Q = kiA, hydraulic gradients inducing flow in the bases are limited to small amounts, usually 0.01 or less. And, the cross-sectional area through which water is escaping laterally is limited to the thickness of the base drainage layer. Because of these compounding factors (see also Chapter 7, "Fundamental Considerations in Subsurface Drainage"), most of the "standard" base materials and filter materials in use have exceedingly low drainage capabilities.

Figure 25, which was prepared with Darcy's law, shows the drainage-effectiveness of some "standard" base materials, in contrast with those of some highly permeable open-graded AC mixes or crushed rock bases. Infiltration rates that can be removed by materials of several permeabilities are shown in relation to the widths of the pavements being drained. The base drainage layer is assumed to be 0.5 ft thick, and its slope of 0.01 is assumed equal to the average hydraulic gradient in the base drainage layer.

Referring to Fig. 25, it can be seen that the "standard" bases with coefficients of permeability in the range of 5×10^{-4} to 0.01 cm/sec (1 to

30 ft/day), are capable of removing only miniscule rates of infiltration, far below even light rainfall rates. On the other hand, the open-graded materials have within their capabilities the removal of heavy rates of infiltration from very wide runways, aprons, etc.

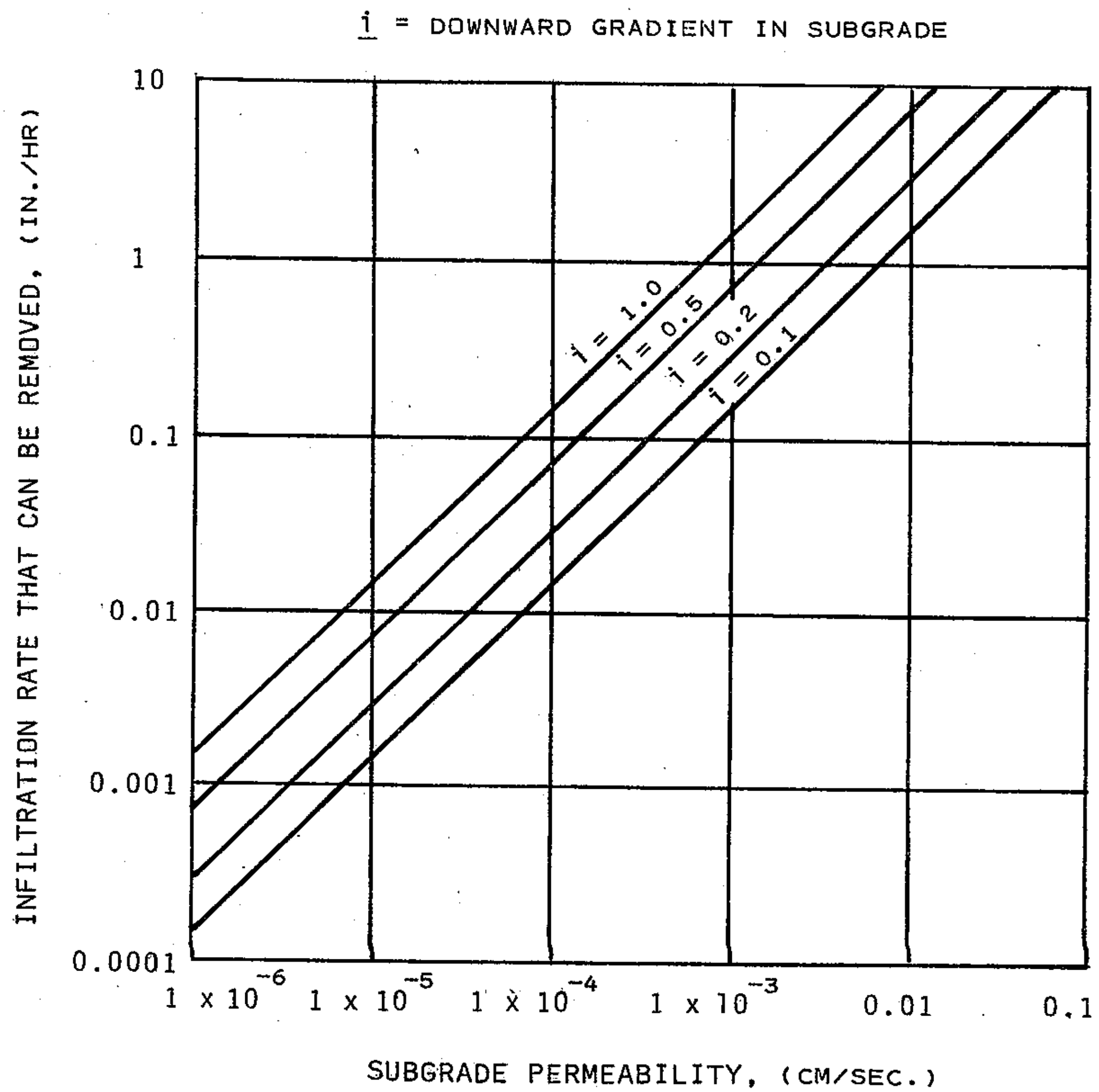

Figure 24. Capabilities of subgrades to remove infiltration.

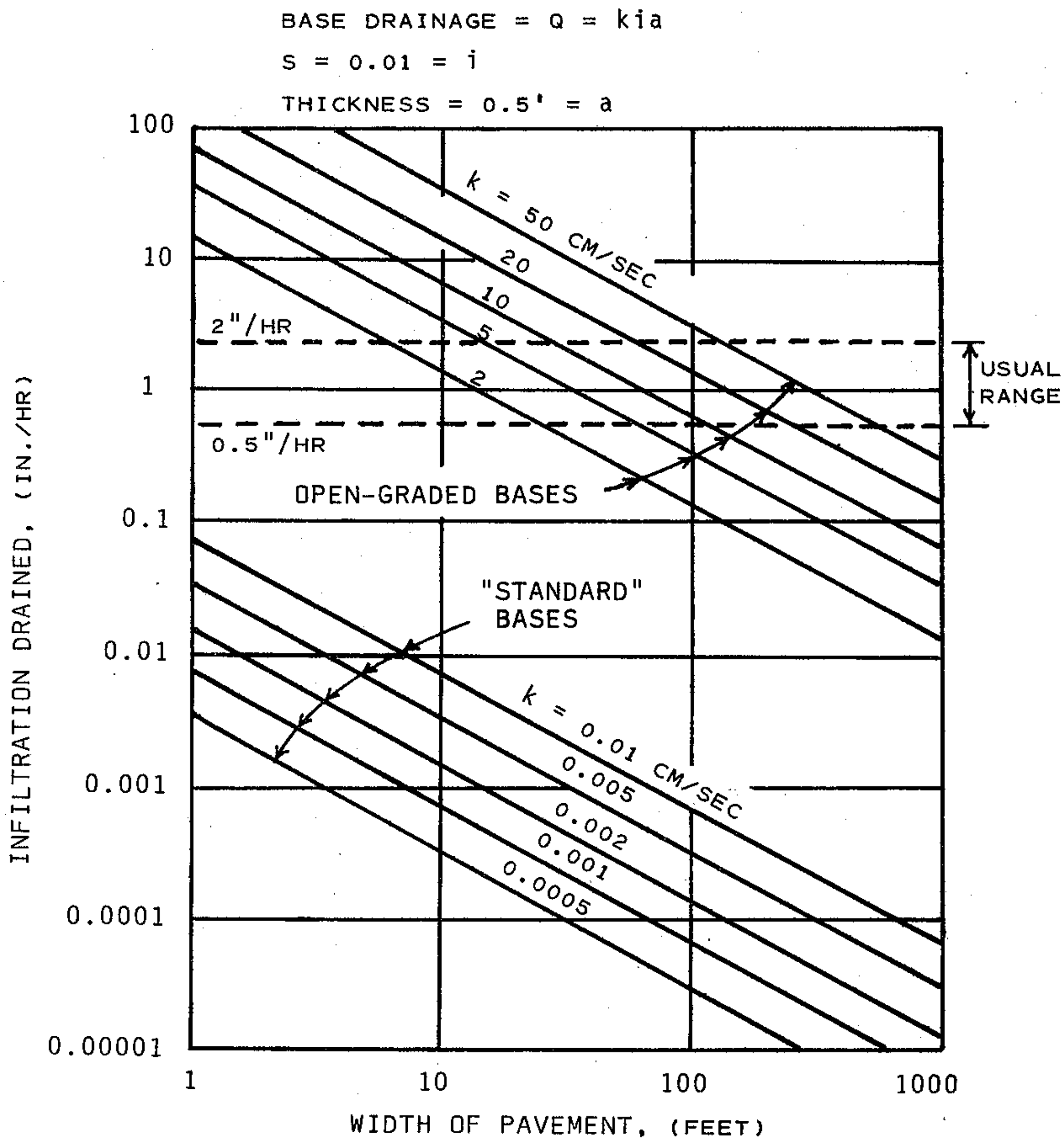

Figure 25. Capabilities of bases with edge drains to remove infiltration (slopes of bases = s = 0.01).

Time for Water to Flow Through Drainage Systems. In cold regions where frost heaving and other problems from freezing of water in roadbeds are important, any water that enters structural sections should be able to flow through the system before it can freeze. This is particularly important in periods of fluctuating temperatures--nighttime freezing and daytime showers. One criterion that has been suggested to minimize problems in highway pavements from cycling temperatures[28] is to make the drainage layers sufficiently permeable so that any water entering cracks, joints, etc. can flow through the base layer and get to pipes within 30 minutes. The wide, flat pavement areas of airfields are more difficult to drain than narrower highway pavements. If a 2-hour requirement were set for airfield pavements this would be a vast improvement over present standards (that are only rarely used). The minimum permeabilities that would be needed for a 2-hour drainage time, as calculated with Darcy's law, are given in Fig. 26 for an effective porosity of 30 percent. Curves are given relating the minimum required permeability with maximum seepage distance for base drainage layers of 0.5 foot, and 1.0 foot thickness. Curves are for slopes of 0.005, 0.010, 0.015, and 0.02. The calculations assume that pipe drains are provided at the outer, lower edges of the pavements being drained, with free gravity drainage. It can be seen that taxiways with a half-width of 37.5 feet could be properly drained (by this criterion) if their bases have coefficients of permeability in the order of 3 cm/sec (10,000 ft/day). But, runways or parking aprons with drainage distances of 150 feet or more would need to have base drainage materials with coefficients of permeability in the range of 10 to 30 cm/sec (30,000 to 100,000 ft/day) for slopes between 1 percent and 2 percent. Some of the data in Fig. 26 are summarized in Table 5, following.

Table 5

Minimum Permeabilities Required in Order to Drain 12-in. Bases in 2 Hours or Less

Slope of Base, %	Maximum Drainage Path, Ft. 50	100	200	300
0.5	4.5 cm/sec (13,000)	12.5 cm/sec (36,000)	33 cm/sec (94,000)	-
1.0	3.5 cm/sec (10,000)	8.3 cm/sec (24,000)	20 cm/sec (58,000)	32 cm/sec (91,000)
1.5	2.8 cm/sec (8,000)	6.7 cm/sec (19,000)	14.6 cm/sec (42,000)	22 cm/sec (64,000)
2.0	2.4 cm/sec (7,000)	5.2 cm/sec (15,000)	11.5 cm/sec (33,000)	17.5 cm/sec (50,000)

Numbers in parentheses are ft/day (see also Fig. 26).

[28] *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections,* Federal Highway Administration (FHWA)(H. R. Cedergren and Ken O'Brien and Assoc., January, 1973).

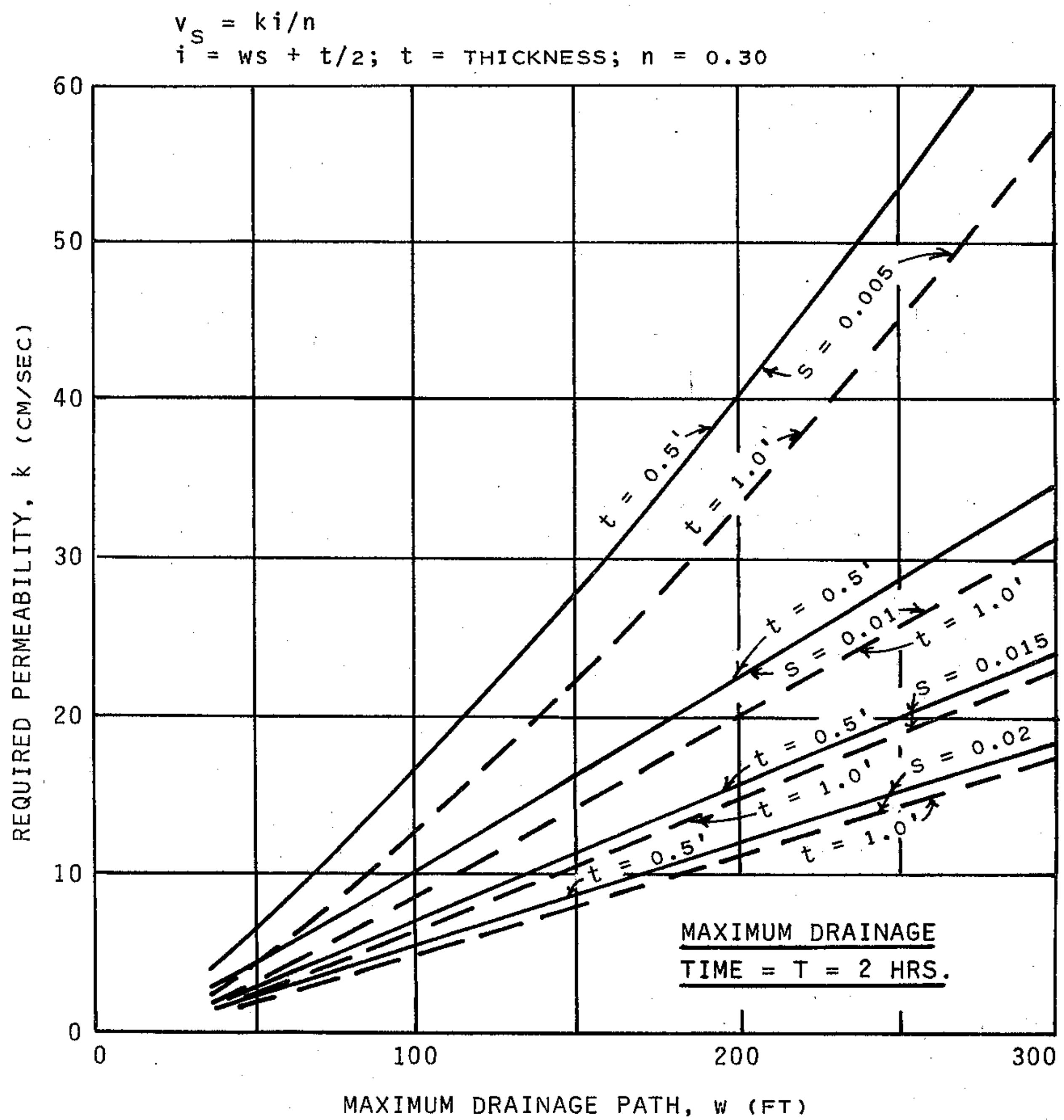

Figure 26. Minimum permeabilities needed in order to drain bases in 2 hours or less ($\underline{n}$ = 0.3).

Figure 27, which is similar to Fig. 26, gives curves for a maximum drainage time of 4 hours. Coefficients of permeability are 50 percent of those needed for a 2-hour drainage time. Some of the data in Fig. 27 are

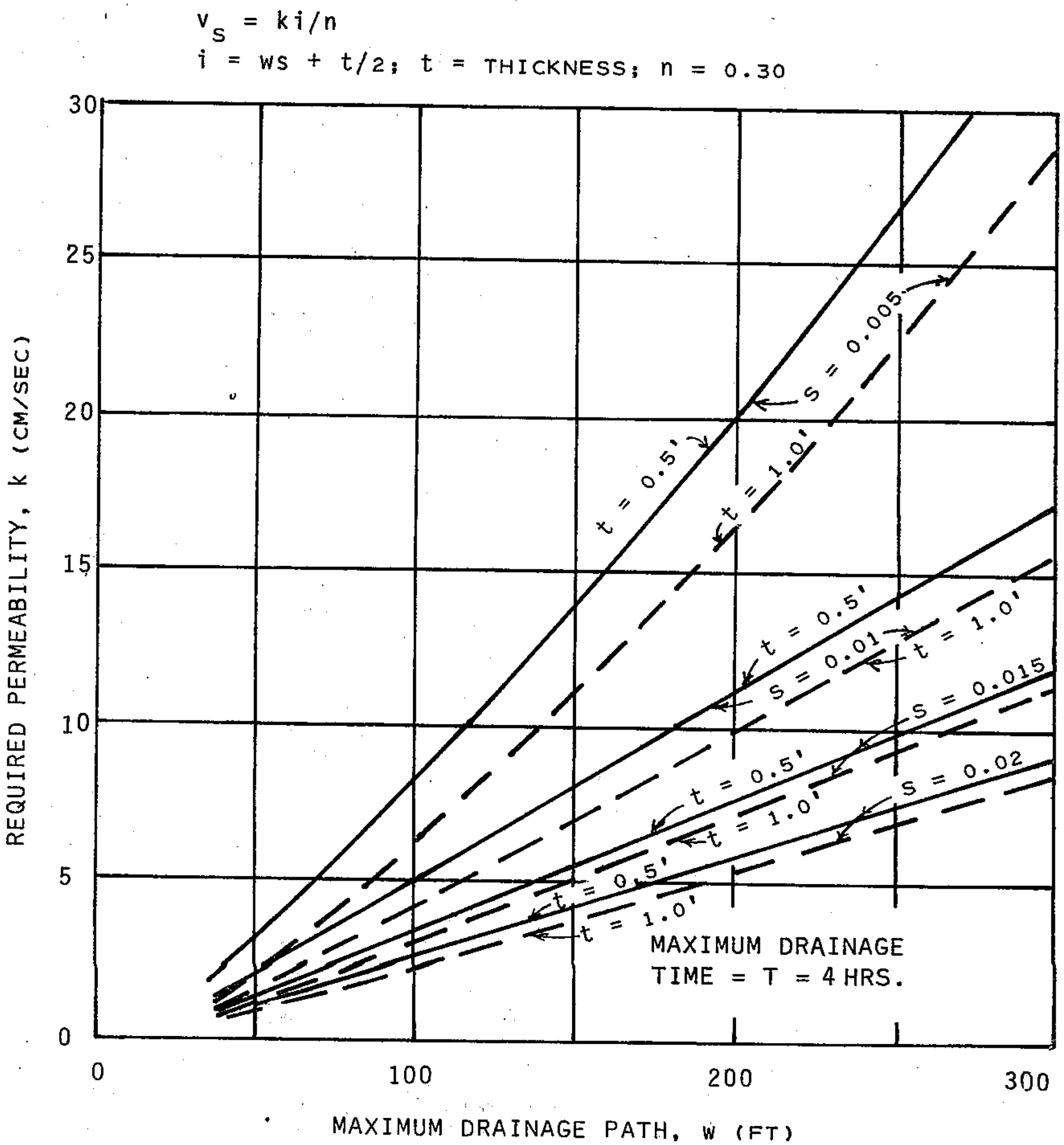

Figure 27. Minimum permeabilities needed in order to drain bases in 4 hours or less ($\underline{n}$ = 0.3).

summarized in Table 6.

Table 6

Minimum Permeabilities Required in Order to Drain 12-in. Bases in 4 Hours or Less

Slope of Base, %	Maximum Drainage Path, Ft. 50	100	200	300
0.5	2.3 cm/sec (6,500)	6.3 cm/sec (18,000)	16.5 cm/sec (47,000)	28 cm/sec (80,000)
1.0	1.8 cm/sec (5,000)	4.2 cm/sec (12,000)	10 cm/sec (29,000)	16 cm/sec (45,000)
1.5	1.4 cm/sec (4,000)	3.4 cm/sec (9,500)	7.3 cm/sec (21,000)	11 cm/sec (32,000)
2.0	1.2 cm/sec (3,500)	2.6 cm/sec (7,500)	5.7 cm/sec (16,000)	8.7 cm/sec (25,000)

Numbers in parentheses are ft/day (see also Fig. 27).

If subsurface drains are to be capable of getting water out within a few hours time, it is evident that the base drainage layers must be constructed of highly permeable open-graded types of materials. Such materials are also very non-susceptible to freezing problems. Obviously, base course materials with much lower permeabilities than those indicated by the curves in Figures 26 and 27 (and Tables 5 and 6) would be very ineffective in protecting roadbeds or airfields from freezing problems caused by excess water in structural sections. Severe pavement distress associated with excess water and cold temperatures was a problem at one of the air bases selected for the detailed field investigations (see Appendix E).

Time-Lag of Fall Saturation in Structural Sections. Application of the first criterion of drainage-effectiveness (quantities of water that can be removed) indicates that most pavements need to be constructed on highly permeable open-graded bases, if normally expected inflows are to be properly removed. Likewise, when the second criterion is applied (maximum seepage time not to exceed a few hours), similar types of materials are needed. When these open-graded types of materials are used (with the necessary pipes), and the drainage layer cannot become completely filled with water, seepage out of the primary pavement layers is vertically downward as these layers are being drained by bottom drainage. When this type of design is used, the buildup of saturation mounds is kept to a minimum and almost does not occur at all; hence the efficiency of this kind of system in preventing exposure to excess water can be nearly 100 percent.

When pavements have no drainage systems and water must be removed by pumping or bleeding through the top by roof drainage, or by seepage into the soil by subgrade drainage, water can stand in structural sections for prolonged periods of time, and the time-lag of fall of saturation can be very slow. When bases of the "standard" types are provided with edge drains, the process may be somewhat faster, but can still be relatively slow.

Since the major damages to pavements take place when free water is contained in structural sections, it is important to be able to add up the total number of hours or days of exposure to excess water per year. At any given location, the total time of exposure is the number of hours of saturating rain plus the total of the time-lags between rains. In areas where there are frequent rainstorms throughout the year, and the subgrade is highly impermeable, the total time of exposure to excess water may equal or approach 365 days a year. A detailed study of rainfall records at a given locality is necessary to determine total hours per year of exposure to saturating rains. The time-lag after it stops raining is needed to be able to obtain the accumulated hours of exposure to excess water in a year. When the time-lag exceeds an interval between storms, the time of exposure is 100 percent of the intervening period.

When pavements are constructed on base courses having no drains, some drainage of water out of a given pavement may occur by seepage to lower areas along the profile, to outer edges, and by leakage or pumping out of cracks and joints. If the subgrade is highly permeable, the primary drainage may be downward into the soil, but if the subgrade is low in permeability, the combined drainage rate may be very slow.

To illustrate the capabilities of subgrades to drain pavements, Fig. 28 was prepared. This chart was derived from Fig. 17, which was developed for the assumption that there is no significant drainage except into the subgrade. Figure 28 assumes a 16-in. thick PCC pavement with cracks and joints totaling 1 percent of the volume of the concrete, on a 12-in. thick, well-graded base with a porosity of 0.10. The general shape of the flow pattern for this condition was illustrated by a flow net in Fig. 16, in which seepage into the subgrade takes place under an average downward hydraulic gradient of approximately 0.20.

Rating the effectiveness of subgrades to drain excess water after it stops raining was based on a drainage criterion of 50 percent lowering of saturation in the base course (see Fig. 28). The times for 50 percent lowering, as obtained with the aid of Fig. 17, are plotted in Fig. 28. The solid, sloping line is for an average hydraulic gradient of 0.2 in the subgrade. The dashed lines are for other values of hydraulic gradient. By referring to Fig. 28, it is seen that if a 50 percent lowering of saturation in the base is to occur in half a day, subgrades must have coefficients of permeability in the order of 1×10^{-3} to 1×10^{-4} cm/sec (0.2 to 2 ft/day) or larger, depending on the effective hydraulic gradient available to discharge seepage into the subgrade. If a shorter time is desired, still higher permeabilities would be needed. In many areas of the United States, natural compacted subgrade soils have coefficients of permeability in the order of 1×10^{-5} cm/sec (0.03 ft/day) or less! In all such areas, subgrade drainage is highly ineffective in removing excess water from pavement structural sections.

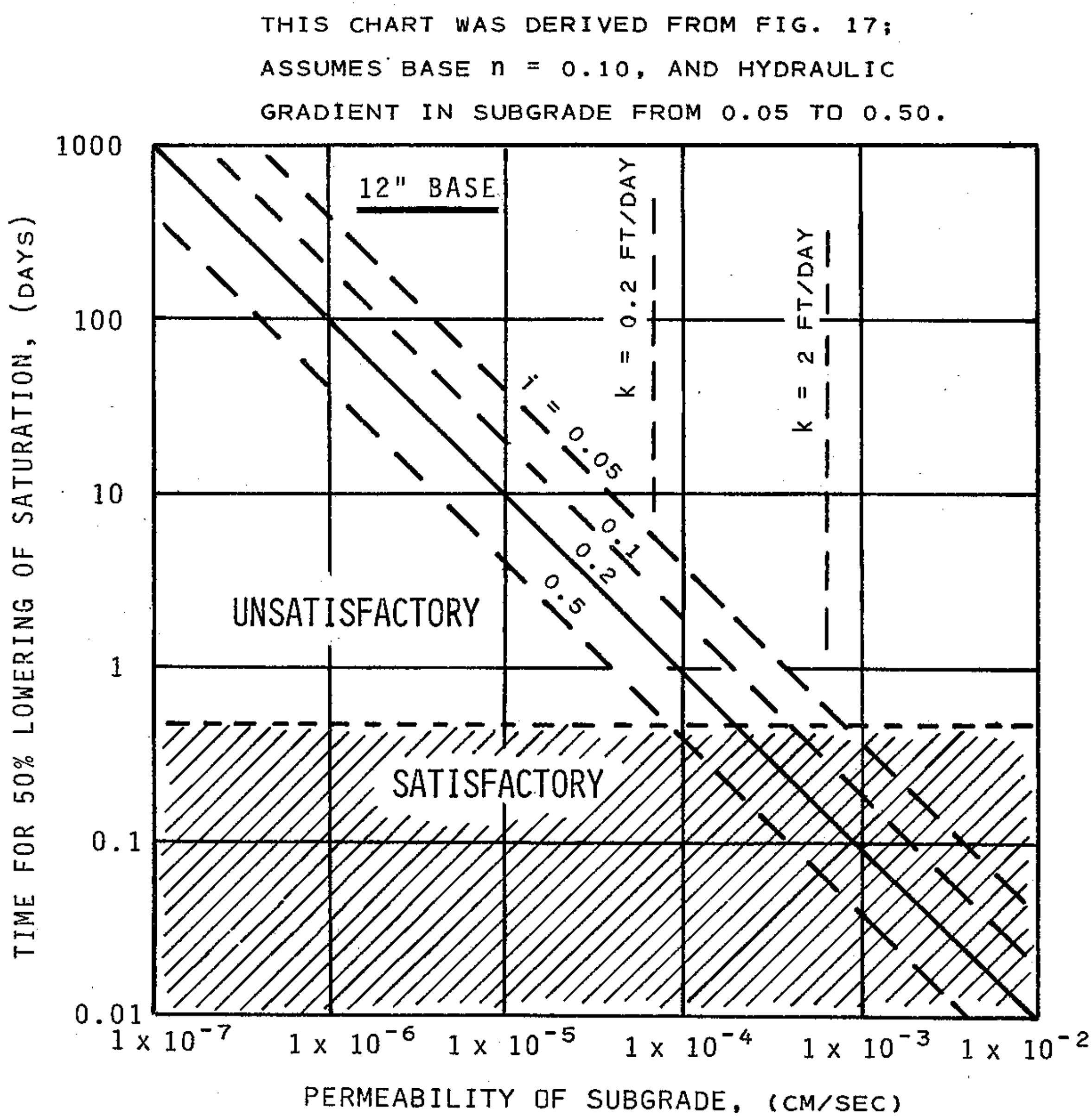

Figure 28. Effectiveness of subgrades in draining bases after stop of rain.

When base courses under pavements are provided with pipe drains for gravity removal of water, a criterion for permeability is given in a

Department of the Army Technical Manual[29]:

$$t = \frac{n_e D^2}{2880kH_o} \qquad \text{[Eq. 7]}$$

In Eq. 7, the term t is the time for 50 percent drainage of a sloping base with a drain along its lower edge, n_e is the effective porosity of the base, D is the sloping width, k is the coefficient of permeability in ft/minute, and $H_o = H + sD$, where H is the thickness of the base, and s is its cross slope. When coefficients of permeability are expressed in cm/sec, Equation 7 becomes:

$$t = \frac{n_e D^2}{5760kH_o} \qquad \text{[Eq. 8]}$$

Using Equation 8, Fig. 29 was prepared to show the amount of time needed for 50 percent drainage of pavements having porous bases 1.0 foot thick, on a slope of 0.01, and an effective porosity of 30 percent. Curves are given for various coefficients of permeability and a range of values of D. It can be seen that if a time of 10 days is used as a criterion (t = 10 days), pavements having a sloping distance of 100 feet or more would need to have bases with coefficients of permeability of about 0.02 cm/sec (60 ft/day) or larger. If a criterion of 1 day were used, permeabilities would need to be 0.2 cm/sec (600 ft/day), or larger. If a requirement of 50 percent drainage in 0.1 day (2.4 hours) were used, coefficients of permeability would need to be in the range of 2 to 15 cm/sec (6000 to 45,000 ft/day), which is comparable to the range required on the basis of the two criteria previously discussed.

Summary Comments: In the preceding portion of this report, the effectiveness of subsurface drainage systems has been rated in terms of both cost-effectiveness and drainage-effectiveness. Cost-effectiveness was expressed in relation to the unit costs of pavements per year of useful service, and in costs per cycle of B-52's using the airfield in an example problem. Drainage-effectiveness was rated in terms of three practical criteria: (1) rates of surface infiltration and other inflows that can be removed, (2) time for water to flow through drainage systems, and (3) time-lag of fall of saturation in structural sections (which can also be expressed in terms of the time to drain structural sections).

The drainage criteria have shown that a high level of effectiveness of

[29] *Technical Manual No. 5-820-2*, "Drainage and Erosion Control--Subsurface Drainage Facilities for Airfields," (Headquarters, Department of the Army, August, 1965).

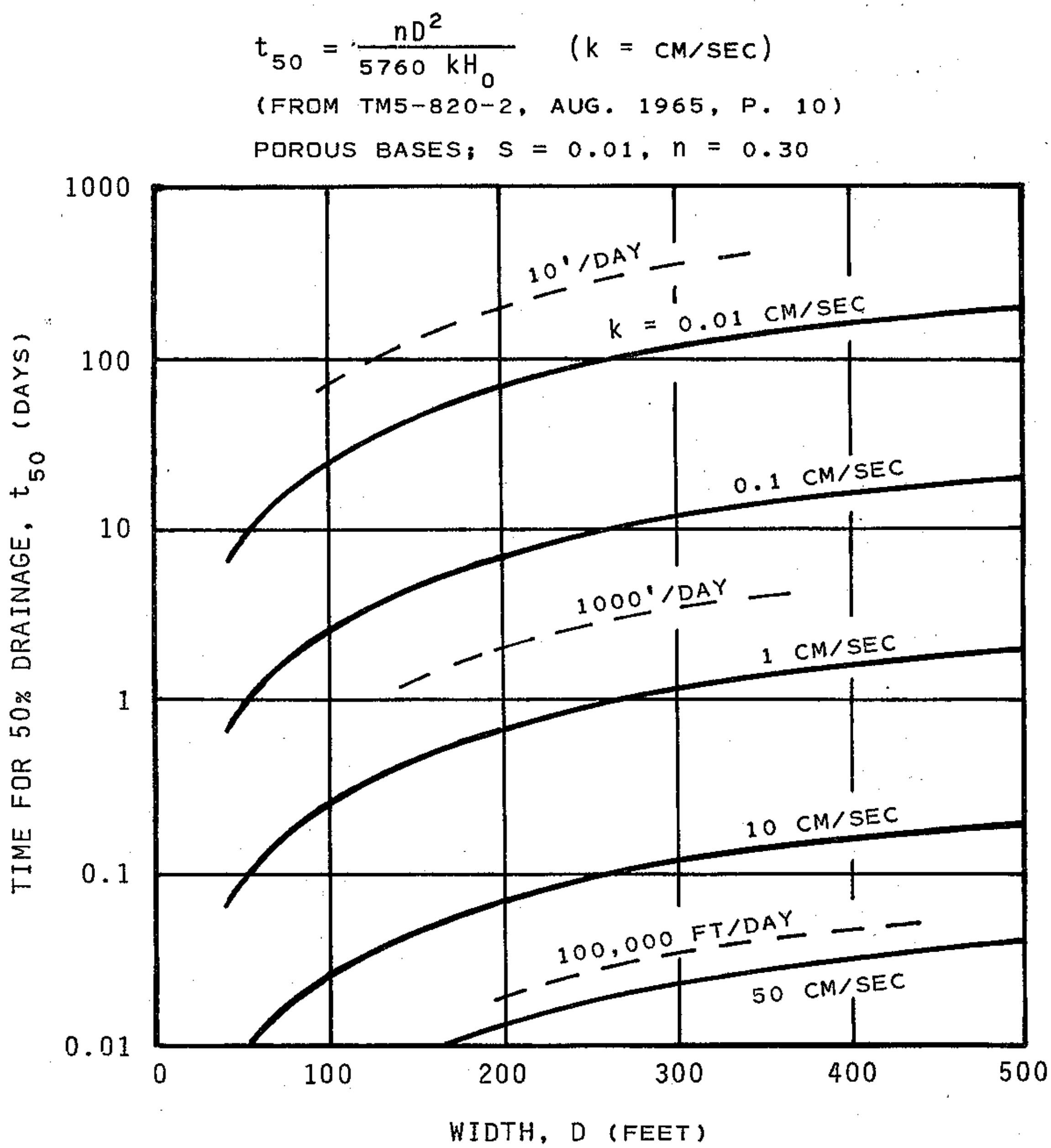

Figure 29. Permeability versus time for 50% drainage of bases with edge drains ($\underline{n}$ = 0.30, $\underline{H}$ = 1.0 ft.).

subsurface drainage of airfield pavements requires the use of highly permeable, open-graded bases under pavements. Systems constructed with materials of this kind appear to offer outstanding advantages in cost-effectiveness as well as drainage-effectiveness. Examples that are given illustrate application of fundamental principles to this kind of seepage and drainage problem. Although simplifying assumptions have been made, it is felt that these solutions provide valid evidence in support of the overall conclusion of this study that rapid drainage of airfield pavements warrants serious consideration in future pavement design, and in all important restorations of failing pavements.

Drainage layers having coefficients of permeabilities of 20 to 50 cm/sec can allow porous AC pavements to absorb heavy rainfall rates (see Fig. 25) without allowing water to build up on pavement areas. Consequently, the use of these highly permeable, open-graded bases under porous pavements could greatly reduce hydroplaning problems in some areas where this is a serious safety problem. It is felt that this approach to the relief of hydroplaning warrants further research.

10 LEVEL AND TYPE OF MAINTENANCE OPERATIONS REQUIRED ON SUBSURFACE DRAINAGE SYSTEMS

Subsurface drainage systems that are correctly designed, and constructed according to adequate plans and specifications, should normally require very little maintenance. Some precautions are needed, however--mainly in the normal maintenance operations at air bases and airfields--to assure that the subsurface drainage systems will function as intended for the life of the protected pavements.

The fundamental principle to be observed is that nothing should be done that could impede the free flow of water through and out of subsurface drainage systems. Also, even when highly efficient subsurface drainage systems are provided, efforts should be made to keep pavement surfaces well sealed, and objectionable amounts of silt, clay, cement, and asphaltic materials should be prevented from entering through cracks, joints, etc. into the drainage layers.

Maintenance operations that are considered of greatest importance to the preservation of the designed outlet capabilities of subsurface drainage systems are summarized in the following paragraphs.

<u>Joint Sealing and Seal Coat Operations</u>. Normal joint sealing and seal coat practices should be continued on a regular basis to minimize the quantities of water or other matter that can enter into the structural section. Even though pavements have subsurface drainage systems capable of removing relatively large volumes of water from surface infiltration, high groundwater inflows, lateral seepage, etc., their surfaces should not be permitted to have large, unsealed cracks or joints which will allow water or foreign matter to enter. And, if the systems should have only marginal capabilities for removing water, it is even more important to try to keep pavement surfaces well sealed.

Cleaning Operations on Pavement Surfaces. Pavement sweeping and other cleaning operations should be carried out as necessary to prevent the accumulation of large amounts of foreign matter of any kind that can be washed into structural sections through joints and cracks. If the geometrics of adjacent land areas are such that soil can erode onto paved areas (usually this cannot occur), particular attention should be given to the prompt removal of any such material, both to reduce skidding hazards to airplanes, and to minimize the entry of such materials into structural sections. If dust storms cause large amounts of fine sand or silt to accumulate on pavements, these materials should be broomed off. When hot or liquid asphalts, emulsions, etc. are used for surface maintenance purposes, large quantities of any such materials should not be allowed to enter through cracks, joints, or holes in pavements, unless there is a specific, planned purpose in wanting such materials to fill cavities or other spaces under pavements.

Outlet Pipes and Markers. Outlet pipes should be inspected periodically (at least once every 3 months) to be sure that they are not blocked by earth, weeds, grass, bird or animal nests, etc., but are fully open for free discharge of any water that reaches them from the subsurface drainage system. When foreign matter is found within or at the end of an outlet where it can impede flow, it should be removed, and the conditions causing it to accumulate should be corrected. Usually outlet pipes should be provided with clearly visible marker posts that can be seen from the edge of the adjacent pavement, but short enough not to create a safety hazard. Plan maps of pavement-drainage systems should show the locations of all outlets and outlet markers. If any are damaged or destroyed, they should be replaced. Mowing operations and other maintenance operations should not be allowed to damage markers or outlets.

General Maintenance Operations. All personnel involved in maintenance operations on or in the vicinity of pavement-drainage systems should be made aware of the presence of the subsurface drainage systems and their outlets, etc., and the need to prevent any blockages that would impede free gravity outflow from the systems. Earth ditches comprising part of a drainage system should be periodically inspected, and the water passageways should be kept clear of high grass, weeds, brush, trees, eroded soil, or any other matter that can impede the flow of water out of and away from pavement drainage systems. Appurtenant structures such as lamp holes, manholes, splash blocks, drop structures, etc., should be periodically inspected and any significant damages or insufficiencies should be repaired or corrected.

11 DAMAGES LIKELY TO OCCUR IF MAINTENANCE IS NEGLECTED

When subsurface drainage systems are provided for airfield pavements, free gravity flow of water out of the systems must be continuously maintained. Subsurface drains are almost completely interior elements which do not normally require any maintenance. Only the collector pipes, exit pipes, outlet markers, etc., may need occasional maintenance to correct accidental damage, blockage, or siltation that might impair discharge flows. Some of the effects of maintenance on drainage discharge pipes, markers, etc., are discussed in Chapter 10, "Level and Type of Maintenance Operations Required on Subsurface Drainage Systems." Suggestions were made regarding the need to keep pavement surfaces well sealed and maintained, and to coordinate normal airfield maintenance, mowing operations, etc., so as not to damage the exit features of subsurface drainage systems.

If outlets of subsurface drains are blocked, water that gets into these systems becomes trapped, resulting in about the same conditions that would exist with no subsurface drainage system. Highly permeable base drainage layers with no outlets or with blocked outlets will allow water to flow by gravity to lower elevations, and generally will provide some protection to the crown areas of pavements even under these conditions, but may allow the buildup of artesian pressures under pavements at lower elevations.

Pavements provided with subsurface drains and pipe outlets should have the locations of all outlets marked with suitable stakes and identification labels,and all locations should be marked clearly on a plan drawing of the pavements. During the site inspection trips, cases were mentioned where pipes from underdrains, and grated inlets, had been completely buried by filling operations, by soil erosion, or other actions or activities which covered pipes and outlets, by debris, thick grass and sod, etc. In one case, according to the local engineers, some grated inlets had been covered over for so many years that the present maintenance personnel had no recollection of having ever seen these facilities. After examining construction drawings of this airfield, locations of "designed" inlets were located and spotted in the field. After some digging and prodding, a number of inlets were located and uncovered, much to the surprise of those working at the base at the time.

If pavement cracks and joints are not kept reasonably well sealed, or surfaces develop depressions or other water traps, large amounts of water may enter and tend to overload drainage systems that have only marginal capacities for removing water. This will reduce the benefits that could be obtained from these systems to levels below those possible if inflows are kept to minimums.

If large amounts of mud, silt, cement, or asphaltic repair materials, rubber solvents, etc. are allowed to enter into structural sections, local clogging of drainage layers may occur, at least partially nullifying the benefits that could be obtained from these systems.

Some of the problems cited are considered less likely to damage pavements when they have been provided with subsurface drainage systems having high discharge rates. Nevertheless, it is felt that maintenance standards should not be lowered because it is known that a particular air base has a very comprehensive subsurface drainage system.

If porous AC pavements are placed on highly permeable base drainage layers to reduce hydroplaning problems (see "Summary Comments" section of Chapter 9), seal coats, fog seals, slurry seals, etc. should not be applied, as these treatments would slow down the infiltration rate and could nullify the hydroplaning benefits of these pavement drainage systems. These hydroplaning benefits could not be maintained for long in areas where large amounts of rubber accumulate on the pavement surface.

12 CONCLUSIONS AND RECOMMENDATIONS

On the basis of the information gathered in this study, together with the analyses that have been made, the following conclusions and recommendations are presented.

Conclusions.

1. Most of the airfields in the United States are constructed on stabilized or unstabilized bases which are generally slow draining, and only in special cases are subdrains provided (mainly in cold regions to drain thick granular bases).

2. Keeping pavements tightly sealed is virtually impossible, and relatively large amounts of water can enter through most pavements after moderate lengths of exposure to the elements (in spite of all hopes to the contrary).

3. Rainfall rates in most areas of the United States are higher than the drainage capabilities of subgrades (particularly after being compacted, and sometimes sealed under pavements), with the result that more water is available to enter into many pavements than their subgrades are capable of draining out; hence, undrained structural sections may contain excess water many months each year. In arid climates the length of exposure to free water per year may be quite minimal, but in some areas that are classified as "semi-arid," (see Appendix C, for example), significant water problems may develop.

4. During the periods of time that structural sections are required to carry heavy loads while filled with water, the rates of damage may be many times greater than at other times when no free water is present.

5. In evaluating the effectiveness of the various methods that can be used for draining water out of structural sections, this report categorizes the available systems according to the direction of flow of water out of the sections. The report shows that the most commonly used pavement systems depend primarily on drainage out through the top or sides of the pavements, which is highly inefficient. By changing the systems to allow water to escape from primary pavement layers by downward flow, discharge rates can be vastly increased, and the effectiveness of the drainage systems

increased hundreds to thousands of times! Downward flow is the most effective kind because it works with nature to the fullest possible extent, making maximum use of gravitational forces to drain structural sections.

6. Utilizing the principles noted under Conclusion 5, the report shows that the detrimental effects of excess water can be kept to a minimum, by providing heavy-duty pavements with coarse open-graded Macadam types of base drainage layers, fitted with collector pipes and outlet pipes that prevent major accumulations of water in pavements.

7. Evaluations of the drainage-effectiveness of pavements by three different criteria, show that the normally used designs and materials provide only minimal levels of protection against exposure to excess water.

8. A potential side benefit of the use of the coarse, open-graded Macadam type of drainage layer under porous AC pavements is the possible reduction in hazards to planes in areas where hydroplaning is a critical safety problem.

9. Studies of the potential long-term costs of pavements (including original costs and all significant maintenance and restoration costs), indicate that well drained pavements will generally be more cost-effective than slowly draining pavements (see sample calculations in Chapter 9). Other calculations made in studies of the relative costs of poorly drained and well drained highway pavements[30] led to the same conclusion. The cost of constructing well drained pavements may vary from location to location and the relative merits of conventional pavement systems versus drained pavement systems should be evaluated for the actual site of proposed construction.

10. Most of the heavy-duty pavements in use were liberally designed, and show only minimal damages after 15 or 16 years of service. Yet, the ultimate life expectancy of these pavements (both in terms of years of service and numbers of traffic cycles) could be greatly increased in many cases by rapid drainage of excess water out of their structural sections.

Recommendations. In consideration of the information compiled in this study, the following recommendations are offered:

1. Accelerated traffic tests be made with apparatus of the kind operated by the University of Illinois (its circular test track) to test the serviceability of very permeable, open-graded bases of various gradations,

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[30] *Final Report,* Studies for the Development of "Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections," Federal Highway Administration (FHWA)(H. R. Cedergren & Ken O'Brien & Assoc., February, 1973), pp. 158-179.

both untreated and mixed with hot asphalt, under several thicknesses of wearing courses.

2. The potentially greater service life and reduced repair costs of the well drained pavements be introduced in the life cycle costing techniques used by CERL. Specifically, it is felt that comparisons should be made of long-term costs of conventional undrained pavement designs with an assumed design life of 20 years or so, versus drained designs of about equal amounts of paving materials, but with probable effective lives of 25, 30, or 35 years, both in areas where "D" cracking is a major problem, and in areas where this kind of damage does not occur.

3. When major reconstructions are required at some of the bases, involving digging out and replacing portions of taxiways, runways, or aprons, some of the reconstructions be made utilizing extremely permeable, open-graded base drainage layers with collector pipes and outlet pipes, to gain experience with this type of pavement system.

4. In the current revising of Corps of Engineers design manuals or subsurface drainage manuals, it is suggested that the drainage concepts brought out in this report and in the recent FHWA drainage booklet[31] be taken into consideration.

5. In this current study, a program of installation and reading of observation wells in pavements at selected airfields provided some very interesting and useful information about the occurrences of excess water in structural sections. It is suggested that CERL consider having additional installations made under other programs for monitoring the rise and fall of saturation within the structural sections at a number of major air bases. It would be very desirable to have some pore pressure measuring instruments put in for measuring transient buildup and fall of pressures under passing aircraft wheels, as well as some simple observation wells of the general type used in this study.

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[31] *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*, Federal Highway Administration (FHWA)(H. R. Cedergren and Ken O'Brien & Assoc., January, 1973).

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APPENDIX A

Summary of Information Gathered From Pavement Evaluation

CONTENTS

TABLES

1 COMMENTS

This Appendix gives a list of the various official reports that were studied at the beginning of this project, to determine the possible degree of effectiveness of drainage systems in use, and the extent of problems with excess water in pavement structural sections.

As a result of this examination of reports as summarized in Table A-1, it was concluded that surface drainage systems are generally adequate and are given a great deal of study in the design of airfield pavements. But, very few airfield pavements have subsurface drainage systems, except for some with longitudinal pipes along edges of pavements and a few with special drains put in after problems with excess water had developed after construction.

It appears that water problems of varying degrees are being experienced with pavements at about 75 percent of the airfields. Therefore, on the overall, it appears that subsurface draining is a problem of major importance to be considered in the reconstruction of failing pavements and in the development of any future design standards.

Table A-1

Summary of Comments in Reports Studied

(Sheet 1)

Location	Reports Studied	Comments
Louisiana	Pav't Evaluation Report, April 1957; Eval. and Cond. Surv. Report, May 1970	Much joint repairing, asphalt sub-sealing, some cracking (1957); some pavement overloading (1970)
California	Condition Surv. Report, May 1963	Bleeding of some taxiways, PCC pavements generally excellent
Texas	Cond. Surv. Report, April 1960; Pavement Eval. Testing, 1969	Some distress from trapped water; bleeding joints; has limited subsurface drainage system
Texas	Pavement Evaluation Rep't, Dec. 1959	Newer pavements good to excellent; older are fair to poor
Arkansas	Condition Surv. Reports, Aug. 1961, April 1965	Pavement <u>life study</u> was made; many pavements <u>overloaded</u>; some have pumping joints
Texas	Condition Surv. Report, May 1956	Some pavements overloaded; water running out of joints and failed areas
California	Pav't Eval. Report No. 2, Jan. 1958; Condition Survey Report, May 1963	Pavements range from poor to good; portions of taxiways have failed, others have cracked
Louisiana	Condition Surv. Report, Aug. 1961	Much pumping of pavement joints; considerable maintenance of NW/SE taxiway and NW and SW warm-up aprons
Texas	Condition Surv. Report, Oct. 1958	Pavements generally good to exc.; no water problems noted
Arizona	Condition Surv. Report, Oct. 1958	Newer pavements generally good; others severely overloaded; in a "semi-arid" area

Table A-1 (Sheet 2)

Location	Reports Studied	Comments
Delaware	Pavement Evaluation and Condition Surv. Report, May 1970	Surface drainage needs maintenance; excessive cracking and pumping due to poor drainage
Maine	Condition Survey Report, Jan. 1962	Cracking of heavy load apron and NW/SE Taxiway, some frost heave
S. Dakota	Airfield Eval. Reports, Jan. 1962, June 1971	Spring break-up very critical, has some vert. wells and edge drains, PCC pavements good to excellent
Washington	Condition Survey Report, Oct. 1965	No evident drainage problems, Taxiway 8 overloaded
Kansas	Condition Survey Report, May 1958	Pavements generally good, but some show overloading and distress
N. Dakota	Rigid Pavement Condition Survey Report, June 1960	Some pavements cracked, but most are excellent, no evident pumping
Texas	Field Performance Investigation, April 1969 (WES)	Impervious subgrade puts pavements in "bathtub"; excessive bleeding; distress attributed to water trapped in top part of impervious base
New York	Condition Survey Report, Dec. 1962	Most pavements overloaded in frost melt period
Germany	Pavement Evaluation Report, May 1972	Has had major repairs; needs some overlays; field is fully operational
Utah	Pavement Evaluation Report, No. 2, April 1958	Hangar pavements on coarse drainage rock (2-in. to 3/8-in.) excellent; other pavements fair to excellent
Korea	Pavement Eval. and Cond. Survey Report, March 1972	Much free water sandwiched between pav't surfaces and also in bases; carrying capacity very limited

Table A-1 (Sheet 3)

Location	Reports Studied	Comments
Virginia	Condition Survey Report, Sept. 1966	Extensive maintenance and reconstruction; thicker PCC good; floods during heavy rainfalls
Nebraska	Condition Survey Report, Dec. 1965	Most pavements O.K.; substantial deterioration & cracking of others
Arkansas	Cond. Survey Reports, Nov. 1961, Sept. 1962, May 1965; Field Performance Invest., Dec. 1968 (WES)	Much trapped water, pumping, bleeding; severe distress of some pavements; much maintenance; ineffective drains
Ohio	Pavement Evaluation Report, Feb. 1955	Many pavements fair to poor, much pumping and cracking, poor drainage
Maine	Condition Survey Report, March 1962	Perforated pipe edge drains in thick non-frost bases; some pavement overloading; heavy pavements generally excellent
Florida	Condition Survey Reports, May 1960, Oct. 1964	Some distress between surveys; cracking problems; precast concrete inlet grates replaced with steel
Montana	Condition Survey Report, March 1961	Perf. pipe edge drains; some bleeding joints; PCC good to excellent; no abnormal maintenance
California	Pavement Condition Survey Report, Nov. 1962	Most PCC pavements good to excellent; patching and some reconstruction
California	Pavement Eval. Report No. 7, Jan. 1959	Primary pavements in good cond.; some surface drainage problems
California	Condition Survey Report, June 1959	1953 pavements generally good; others poor to failed; much trapped water in pavements

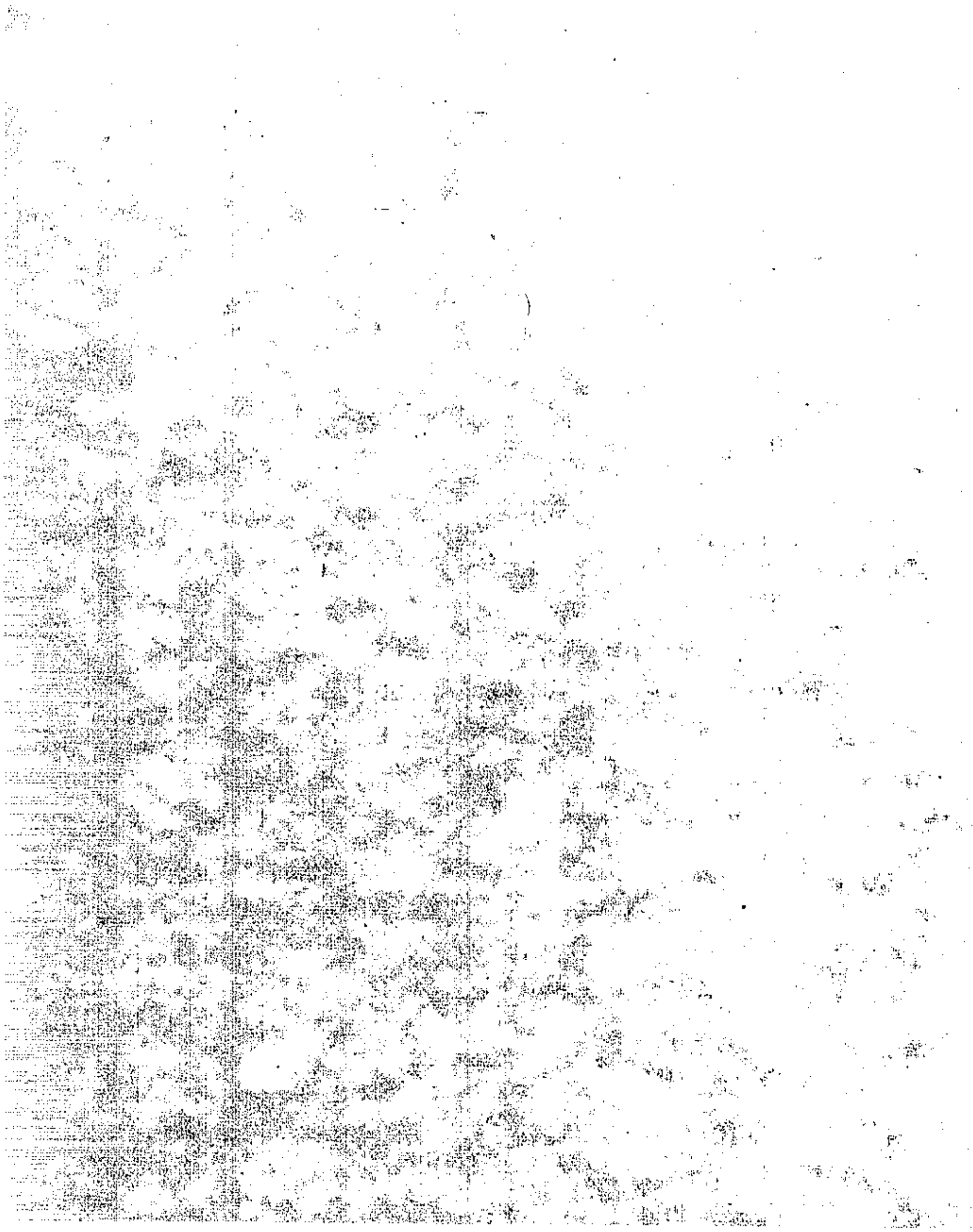
Table A-1 (Sheet 4)

Location	Reports Studied	Comments
New Jersey	Airfield Eval. and Cond. Survey Report, Sept. 1970	Much internal flooding; drainage needs improvement
Idaho	Pavement Condition Survey Report, May 1961	No subsurface drainage system; many pavements overloaded
Korea	Pavement Eval. and Cond. Survey Report, March 1972	Poor bases and construction have caused rapid failures
Massachusetts	Pavement Eval. and Cond. Survey Report, May 1971	70% of pavements in good to exc. condition; others need replacement
New Hampshire	Pavement Condition Survey Report, Jan. 1964	Subgrade generally free draining; heavy repair work on some pavements; some drains put in, 1962
New Hampshire	Drainage Facilities Performance Study, Nov. 1966 (WES); Pavement Eval. Report, Jan. 1972	Soil infiltration into pipes has been a problem; much free water between pavement and base limits allowable loads; cracking and bleeding of joints
Georgia	Pavement Cond. Survey Reports, Nov. 1962, and Oct. 1964	Shoulder slopes too flat; water ponds on some pavements; heavy pav'ts generally O. K.; distress in B-52 apron
Michigan	Pavement Cond. Survey Report, March 1958	Very little traffic, pavements in excellent condition
Germany	Pavement Eval. Report, June 1972	Most pavements in good condition, but overloading can be expected
Germany	Partial Pavement Eval. and Cond. Survey Report, March 1972	Pavement thicknesses and base strengths less than assumed in design; drainage needed in all future designs

Table A-1 (Sheet 5)

Location	Reports Studied	Comments
California	Pavement Cond. Survey Report, April 1970, Naval Civil Engineering Lab.	Much water trapped in pavements; severe deterioration of some pavements shows in photos
Texas	Pavement Cond. Survey Report, April 1971, Naval Civil Engineering Lab.	Much trapped water in pavements; some pavements severely damaged
Massachusetts	Pavement Eval. Report, Sept. 1953; Pavement Cond. Survey Report, Sept. 1964	Heavy pavements good to excellent; overlays fair to good; has sandy subgrade
Germany	Pavement Evaluation Report, Dec. 1971	Pavements have been upgraded since 1968; most pavements are fair to excellent
Ohio	Pavement Evaluation Report, 1960	Heavy duty pavements in excellent condition (Note that a large amount of "D" cracking has occurred since 1960)
Spain	Pavement Eval. and Cond. Survey Report, June 1972	Pavements very good to poor; some are overloaded and badly cracked
Germany	Pavement Evaluation and Cond. Survey Report, Feb. 1972	Many pavements are overloaded; some are totally failed and should be rebuilt with new drainage

NOTE: Comments in this tabulation summarize pertinent comments, conclusions or information presented in the various reports listed.



APPENDIX B

Airfields Examined During Site Inspections

CONTENTS

FIGURES

FIGURES (CONT'D)

FIGURES (CONT'D)

1 GENERAL COMMENTS

This Appendix contains descriptions of the airfields inspected, and photographs selected to show typical kinds of conditions and problems observed during site inspections completed as part of this study. Primary emphasis on surface drainage facilities and problems, on the problems of keeping joints and surfaces well sealed, and on bleeding, pumping, joint damage, cracking, spalling, and other evidence of pavement distress where excess water is at least a contributing factor.

General descriptions of the airfields are given in Section 2, and selected photos are given in Section 3.

2 DESCRIPTIONS OF AIRFIELDS INSPECTED

Airfield A.

Site Inspection: On September 21, 1972, the writer, accompanied by Engineers and the Operations Officer, made a visual inspection and took photos of pavements and drainage structures at numerous locations throughout the main pavement system. Later, this airfield was selected for one of the Field Investigation sites, and on October 31, 1972, seven observation wells were drilled into selected pavements for observation of saturation mounds in the structural sections. One additional well had been installed early in 1972. Several follow-up trips were made to the base by the writer for additional observations during and after extensive rainfalls. Several sets of readings were made in the observation wells over the period of investigation. The results of that field study are summarized in Appendix C.

Description of Air Base. This airfield is located in a "semi-arid" climate, with an average annual rainfall of about 18 inches. Winters are mild. The subgrade soils are primarily clays and clay gravels of low permeability, so natural drainage is slow, and trapped water has been observed in pavements at lower elevations at the airfield for many years. Heavy B-52 bomber traffic has used the field. Although there is little evidence of structural damage, there have been extensive joint sealing and repair problems in areas where water remains in the structural section for prolonged periods of time. Some of the engineers interviewed expressed the belief that in some heavy traffic areas where drainage is poor, PCC slabs are working up and down under the pressure of heavy planes and the damaging actions of trapped water at the interface between the PCC pavements and the base are shortening the life cycle of the pavements. Under the weight of heavy bombers, water can be seen bubbling up from joints in the thick PCC pavements in some areas, according to the engineers at the base.

Extensive diamond-grooving of the runway was done in 1967 to increase friction factor on dry pavement and reduce hydroplaning during heavy rainstorms, which do occur a number of times each year, even though the total annual rainfall is moderate.

Surface drainage is generally good, except for some low areas and other areas where cross slopes of wide pavements are very flat and water collects on the surface for appreciable amounts of time during and after each shower or rainstorm. Largely, surface water flows off paved areas into inlets in adjacent land and into storm sewers, or ditches which remove it to natural drainage courses.

Several of the photos taken at this air base during various visits to the site are included in this appendix, which illustrates important types of conditions and problems at air bases.

Airfield B.

Site Inspection. On August 28 to 30, 1972, the writer accompanied a Waterways Experiment Station pavement condition survey team while the team made its survey of important pavements at this air base.

Description of Air Base. The air base is located in a rather heavy rainfall area (annual rainfall about 40 inches), with cold winters (528 deg. days). Its pavements were constructed on subgrade soils which are primarily sandy clay to lean clay. These soils are very impermeable, and provide negligible downward drainage. Poor nautral drainage, combined with the use of slow draining bases or no bases at all under some pavements, created the setting for the retention of water for prolonged periods of time in the pavements and bases, as evident from extensive bleeding and staining in many areas, and severe damage to many pavements. There is extensive "D" cracking of most PCC pavements, including the 24"-27"-24" heavy duty pavements on the main runway and some taxiways, etc. Many PCC pavements have been overlaid--some with 3-in. to 6-in. thick AC overlays, and some with PCC overlays. Some of the older pavements, severely damaged and extensively repaired in the past, are not presently being maintained or used by aircraft.

Extensive internal flooding of most of the pavements throughout this base appears to have taken place over the years. One of the engineers commented that one apron had been badly damaged by B-47's some years ago. He said that when the heavy planes moved over the pavements, water squirted out of cracks and joints, often rising as high as the tops of the planes.

The slow drainage of water out of pavements and bases on low permeability subgrades frequently is evidenced by grass and weed growth in cracks and joints at outer edges of many pavements. Such conditions appeared to exist at this base. High sod at the pavement edges also appeared to be slowing down the flow of surface water from some of the pavements.

Engineers that we talked with expressed the belief that the lengthy retention of water in the pavements may be an important factor contributing to the extensive "D" cracking of the PCC pavements. Water was flowing like an artesian spring out of a major blow-up on an old runway. It had rained heavily a few days prior to this visit, and no doubt water that soaked into this runway at higher elevations was flowing downgrade in joints, cracks, and void spaces, and some was emerging at this blow-up.

It appears to the writer that some portion of the maintenance and replacement costs at this field can be attributed to insufficient subsurface drainage, although a mission change that occurred after design and construction of the facility led to severe pavement overloading which was the direct factor causing pavement distress.

Blow-ups, at the minimum, create a high degree of roughness of pavements, even after being dug out and repaired, which is an inconvenience to plane operations. Pavement fragments and aggregate particles from the blow-ups, if not detected and removed in time, can cause damage to jet aircraft. In severe cases, blow-ups may represent a direct hazard, as one of the engineers said he had actually seen a blow-up take place. He said it was very sudden and violent, like a dynamite explosion. It appears, however, that many of the blow-ups are slow creep actions. Nevertheless, they represent a very serious problem to the use and maintenance of airfield pavements.

Ditches in turfed areas are used for conveying surface water to outflow ditches or storm drain pipes. There are many grated inlets in aprons and other paved areas, but almost no drop inlets in non-paved areas. On the whole, the primary paved areas appear to be well drained with only limited ponding. In some places, however, water gets trapped at the edges of pavements by high sod, as already noted, and cannot get to the drainage system without prolonged flooding of these areas.

Airfield C.

Site Inspection. On September 20, 1972, the writer, accompanied by a Pavement Engineer and a representative from the Operations Office, examined airfield pavements throughout this facility. Detailed conditions were examined at many locations, and photos were taken of representative conditions. Some of these photos are included in this appendix.

On November 1, the writer joined a Waterways Experiment Station team for about a half day while they inspected some pavements at this air base. We discussed general findings of their surveys and some of the observations that have been made by the writer under this contract with Construction Engineering Research Laboratory (CERL).

Description of Air Base. This air base is located in a rather light rainfall area (about 18 inches annual rainfall) and with mild winters. Its subgrade is primarily clayey sandy gravel or clayey gravel of relatively low permeability; hence downward drainage is slow. Trapped water has caused severe distress of isolated pavements, and there have been joint spalling and sealing problems, but the heavy-duty pavements constructed in 1957 and 1958 are in good structural condition. Some joints in the PCC pavements appeared very tight, but many are not. Some experimental work has been done with "new" types of joint sealers. One in particular appears to be vastly superior to regular sealers.

There appeared to be some deep-seated cracking of the AC section of the runway adjacent to a PCC section; and some cracking of the PCC pavement which might have been caused by insufficient compaction of the subgrade according to the Base Pavement Engineers.

Spalling at edges has been somewhat of a problem with the PCC pavements. Epoxy repairs by contract have not always been entirely satisfactory as the patches are sometimes not properly sawed at joints between PCC slabs, with the result that the epoxy patch tends to pull away from both slabs. When epoxy repairs are made by the Base Civil Engineer's forces, a corrugated cardboard joint filler is set in deep enough to separate the patches at joints, and this has been quite successful in preventing the break-out of the patches.

Surface drainage is generally good, with the exception of minor "bird-baths" on some pavements. Because of dry summers, non-paved areas are largely unturfed. Some large grated inlets in low areas help to conduct surface water to the storm drainage system. Evidently surface erosion on non-turfed areas has not been much of a problem, as it has not been necessary to clean out the storm sewer pipes.

Airfield D.

Site Inspection. On September 29, 1972, the writer, accompanied by an engineer from the office of the Base Civil Engineer, made a rather brief inspection of some of the more important pavements at this air base. Photos were taken to show pertinent conditions at several locations. A portion of a main taxiway had been dug out (because of failure) and was in the process of being reconstructed. This gave an opportunity to observe a typical base course that was being placed under this reconstruction, and to observe its drainability.

Description of Air Base. This air base is located in a rather light rainfall area (about 18 inches per year), and with mild winters. Its subgrade is predominately sandy silt to sandy clay, and its low permeability provides very slow natural downward drainage. Trapped water has been observed in many of its pavements which have been constructed at various times from 1938 to 1957. Many of the older, thinner pavements have been severely overloaded and damaged. Some have been strengthened; others have been reconstructed. Heavy maintenance costs have been incurred for most of the older pavements, although most of the newer pavements are in good condition. Keeping joints in PCC pavements sealed has been a problem at this base, as can be said about most pavements everywhere.

During the site inspection on September 29, a failed portion of a taxiway was being reconstructed. Rainwater had entered the trench after the base course had been placed and compacted, and given an asphalt seal. Although there had been no rain for several days, water was still standing on parts of the base course, indicating that the low permeability of the subgrade, combined with the asphalt seal, reduces water penetration to a low rate.

Surface drainage appears to be generally good, with the exception of minor "birdbaths" on some pavements. Numerous grated inlets were provided in both paved and non-paved areas to get water into the storm drainage system. A number of inlets that were examined appeared to be in excellent condition.

Airfield E.

Site Inspection. On August 21, 1972, the writer accompanied a Waterways Experiment Station condition survey team while the team made its survey of important pavements at this air base. Later, this airfield was selected for one of the Field Investigation sites, and on November 9 and 10, 1972, wells were installed in selected pavements for observation of saturation mounds in the structural sections. The results of that field study are summarized in Appendix D.

Description of Air Base. This air base is located in a rather heavy precipitation area (annual rate about 40 inches), with severe winters (1100 deg. days). Its subgrade is a sandy type of soil, and natural drainage appeared to be better than at most of the other air bases. Although not designed for B-52 traffic, some of its pavements have been carrying moderately heavy volumes of B-52 traffic with good success. It appeared that the natural drainage might be helping the pavements at this field. For this reason, Airfield E was selected as one of the sites for more detailed field investigations under Phase II of this project. That investigation (see Appendix D) indicated that the sandy subgrade, when thoroughly compacted, is much lower in permeability than had been anticipated, and other factors are probably responsible for the performance of the pavements at this base.

The engineers at this base recognize the need for maintaining good drainage of paved areas, and devote considerable attention to the maintenance of good positive gradients on runways, taxiways, etc. Any depressions in primary pavements are built back to grade to prevent the ponding of surface water. Keel sections have been reconstructed in many of the taxiways, and numerous overlays have been placed. Also, slurry seals have been placed on many pavements, and extensive joint sealing is carried out on a regular basis.

Evidently there are no (or only few) subsurface drains, but the drilling for installation of observation wells (see Appendix D) disclosed that some of the pavements were constructed on extremely permeable bases of "trap rock." It is the belief of the writer that these extremely permeable bases are draining free water down somewhat in central heavy-load pavements, and that this may be contributing to the apparently good condition of many of these pavements. Although it does not appear that these bases contain collector pipes, or were provided with outlet pipes, they evidently cause a rapid drop in saturation in upper pavement layers at higher elevations that is beneficial.

This field appears to have a good storm drainage system, which evidently requires little attention. Except for grass accumulation over some inlets, and minor amounts of surface erosion, there appear to be no maintenance problems of importance. The drainage system includes a large number of grated inlets in areas adjacent to pavements, and in wide pavement areas as well. Most of the pavements are well sloped to facilitate surface drainage, but high sod at the edges of some pavements slows down the drainage from edges of these pavements. Some of the flatter pavements appear to retain surface water for prolonged periods during and after heavy rains, and stains at some joints suggest there may be some internal flooding and occasional bleeding in some areas.

Airfield F.

Site Inspection. On August 31 and September 1, 1972, the writer accompanied a Waterways Experiment Station pavement condition survey team on its survey of important pavements at this airfield. Later, this airfield was selected as a Field Investigation site; and on October 18, 1972, ten observation wells were installed in selected pavement locations for monitoring of saturation mounds within structural sections. On October 19, the writer made percolation tests in the ten observation wells, and started a series of water level measurements, which was continued under contract with a soils engineering firm until several useful sets of readings were obtained. The results of the field study are summarized in Appendix E.

Description of Air Base. This air base is located in a rather heavy rainfall area (annual rainfall about 40 inches) with fairly severe winters (500 deg. days). It has a subgrade of clay over deep gravel deposits. Although all frost-susceptible materials were removed from the foundations of the heavy-duty pavements to several feet below the tops of the pavements and were replaced with local bank-run non-frost-susceptible materials from pits at the lower end of the reservation, the compacted "pit-run" gravels appear to be quite low in permeability. As a result, downward beneficial drainage appears to be almost negligible, as engineers at this base said they often see water seeping out of the joints of primary PCC pavements after heavy rains. For the most part, the pavements are in "bathtubs" and water stays in lower parts of structural sections for prolonged periods of time after rainstorms. Engineers said that when they cored through the PCC on the main runway and other pavements, water often rose to the tops of the core holes after they were drilled, indicating the structural sections contained free water under sufficient head to rise to the surface.

"D" cracking and "blow-ups" are common problems at this base (as is generally true of all PCC pavements in this area of the United States). Engineers at the base said they think these problems are at least partially caused, or aggravated by, excess water in structural sections. The blow-ups occur during warm-to-hot weather and are believed to be caused by heavy expansion pressures due to heat, and excess water that stays in structural sections because of slow drainage. Repairs to the main runway in the past few years included extensive sawing out and epoxy repairing of spalled and deteriorated areas in 1964, at a cost of about 1.3 million dollars; and a 4-inch AC overlay in 1971, at a cost of about 1.5 million dollars.

It appears that "D" cracking and blow-ups may be aggravated by prolonged retention of free water in cracks, joints, and bases under PCC pavements, and that these high repair costs might have been substantially reduced if free water had been drained out more rapidly.

The "D" cracking and blow-ups are a serious nuisance, if not a hazard to aircraft, as loosened material on important pavements can be drawn into jets, damaging or destroying them. Also, the roughness creates problems in the operation of aircraft.

The shoulders of the main pavements, as well as of other less important pavements, are showing extensive cracking and general deterioration, with extensive repairs already made or contemplated. These damages are believed largely caused by frost action on pavement sections containing free water, which is aggravated by the prolonged retention of free water in relatively undrained pavements. Grass and weeds that are growing in cracks and joints in many shoulder pavements, gives evidence to an abundant supply of water that maintains good growth. This condition may be seen in virtually every military and non-military airfield throughout the country.

Slow drainage of pavements at this air base was verified by water level readings that were made in observation wells installed as part of this study (see Appendix E).

The surface drainage system seems quite adequate, and there have been very few problems from silting of drain pipes. Maintenance of the surface drainage system has been virtually unnecessary with the exception of the occasional removal of debris from the lower ends of the field after severe storms that have filled a flood control reservoir below the reservation and covered the lower end of the field with as much as 4.4 feet of water.

Airport G.

Site Inspection. On August 24 and 25, 1972, the writer, accompanied by engineers from the airport Engineer's office, made a site inspection of some of the pavements and current construction. The purpose was to become familiar with a runway that had been reconstructed in 1969, with a "comprehensive drainage system," after this runway had totally failed from excess water and heavy traffic. Although it was not possible to occupy any of the pavements of the runway or its taxiways that were reconstructed in 1969, we were able to see nearby subgrade conditions and the construction of another runway at this airport. Later, this airport was selected as one of the Field Investigation sites, and on November 13 and 14, 1972, the writer was able to physically occupy and examine portions of the 1969 reconstruction, and arrange for observation of outflows from the pipe drainage system by the airport Engineer's office as a means for evaluating the effectiveness of the "comprehensive drainage system" that had been constructed in 1969. The results of this field study are summarized in Appendix F.

Description of Airfield. The airport is located in a rather heavy rainfall area (annual rainfall about 40-50 inches), with mild winters. Its subgrade is a red silty clay of very low permeability; hence natural downward drainage is extremely poor. In 1969, the 10,000-ft x 150-ft runway deteriorated rapidly due to mud pumping and loss of support of the PCC pavements. This led to excessive down time, patch work, and danger of damaging jet engines from stones and other debris on the surface. At some lower elevations at the airfield water remained in the structural section for weeks after the rains, and at a few places it was so forcefully ejected under the weight of heavy planes that one spot was nicknamed "Old Faithful."

In developing a new design, the airport Engineers decided to "go back to the teachings of McAdam," and design a "comprehensive drainage system." A crushed rock ballast course with some blended rock fines was placed on the cement-stabilized subgrade after a herringbone and edge drain system with 16 miles of pipes was installed in the subgrade. Outlets from the pipes discharge into manholes or from pipes on earth slopes. The 16-inch PCC pavement was constructed with 25-ft by 75-ft spacing of joints. After the joints were sawed with diamond cutters, special joint sealing systems were installed. Not long after completion of the runway-taxiway system, engineers noticed that large quantities of water came out of some of the pipes, starting within the first hour after the beginning of a rainstorm, and dropping off rather quickly after tne end of the storm. After 4 years of heavy-duty service, this runway and taxiway system is still very smooth and shows no signs of any structural problems. The airport Engineers feel it is a very successful system. Because it is rather unusual, it was selected as one of the sites for a more detailed field investigation of the efficiency of drainage systems currently in use.

3 PHOTOS ILLUSTRATING MAJOR PROBLEM AREAS

General Comments. Most airfields contain pavements of a wide range of thickness and design, age, overlays, reconstructions, traffic, subgrade, base conditions, relative elevation, and degree of drainage. Also, surface drainage at isolated spots on an airfield often varies from excellent to only fair or poor, depending on the location on each field. Because of the multiplicity of conditions at any given field, and wide variations in the type and amount of traffic, there are equally wide variations in the condition of pavements throughout a given field. The observations that were made under this study had to be limited to some of the more important pavements and the more obvious conditions. The photos given in this part of Appendix B are grouped into several major areas, as follows:

1) Surface drainage facilities and conditions

2) Joint sealing and repair methods and problems

3) Structural damages or weaknesses

4) "D" cracking and spalling problems

5) Bleeding, surging, and other signs of excess water

6) Reflection cracking through overlays.

Surface Drainage Facilities and Conditions. Effective surface drainage depends on rapidly removing water without excessive delay or accumulation on the pavements or their edges. Ideally, pavements should be as steep as practicable, and there should be no depressions for the entrapment of water, and no barriers from overlays, reconstructions, high shoulders or seal to interfere with the free flow of water off paved areas.

There should be no thick sod, grass, or other debris at the edges of pavements to interfere with the flow of water; and ditches, inlets, pipes, etc. should be adequately designed, constructed, and maintained to ensure the rapid removal of all of the water that reaches them. Although these problems can be minimized by careful construction and maintenance practices, interruptions in surface drainage are sometimes caused by losses in grade from densification or consolidation under channelized traffic.

In general, the airfields investigated have good surface drainage systems, but to some degree problems from all of the above conditions can be observed at many of the airfields. Typical surface drainage facilities and conditions that were seen in the Site Inspection phase of this study are illustrated by photos in Figures B-1 through B-10, on the following five pages. Captions briefly describe the conditions represented.

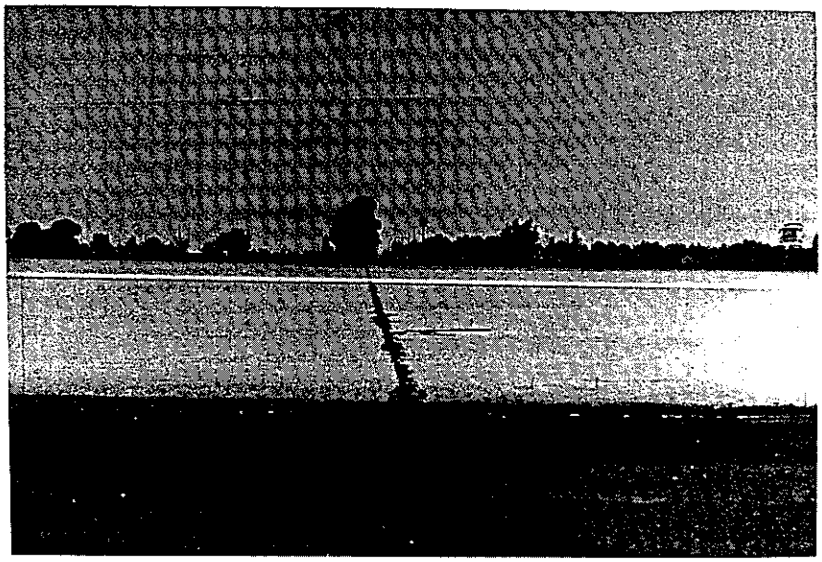


Figure B-1. Low, cross view of crown of a Primary Runway; this crowning is depended on for good surface drainage of many pavements.

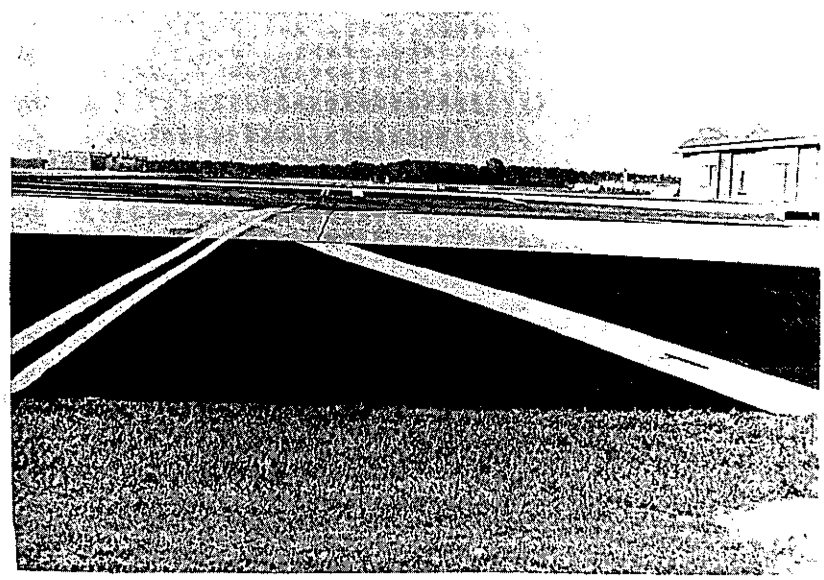


Figure B-2. Low, cross view showing crown of a dock area; it has good cross slope for surface drainage.

Figure B-3. Large "birdbath" in a taxiway leading to an Aircraft Parking Apron; large, wide areas such as this are often very difficult to drain because of limited initial cross slopes.

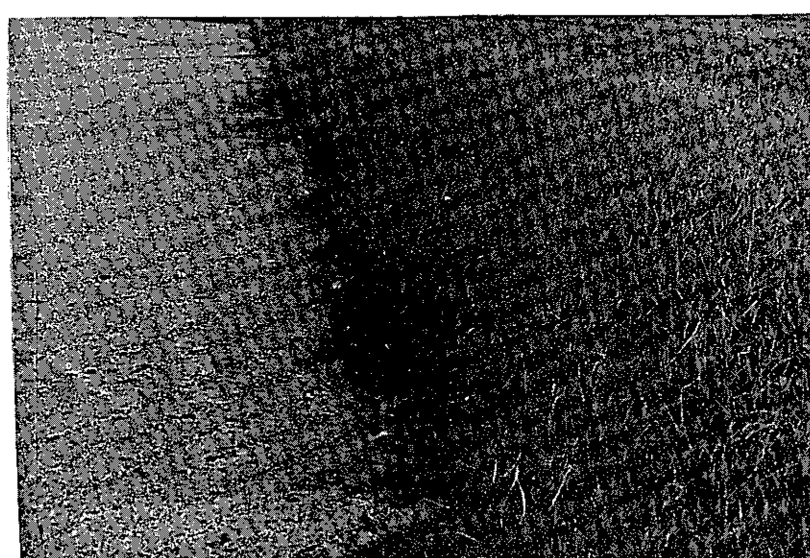


Figure B-4. Low view along edge of a Parking Apron showing high grass and sod which interfere with free drainage of paved area.

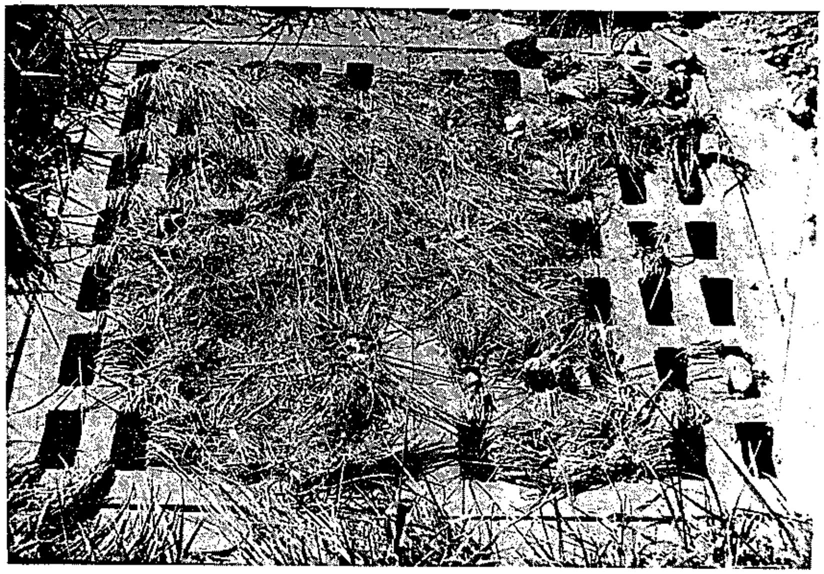


Figure B-5. Grated inlet in grassed area near a taxiway; grass and some gravel may be seen on inlet.

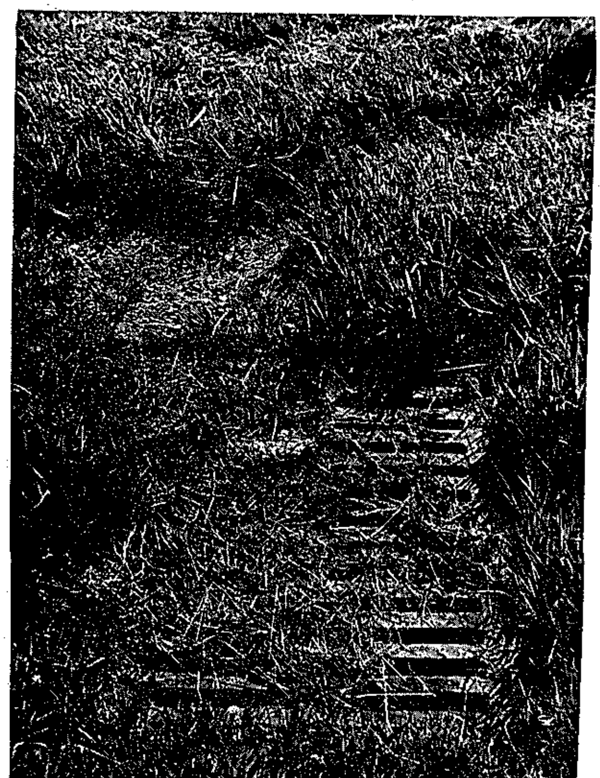


Figure B-6. Grated inlet in grassed area between Stubs; soil near inlet has eroded; cut grass partly covers inlet.

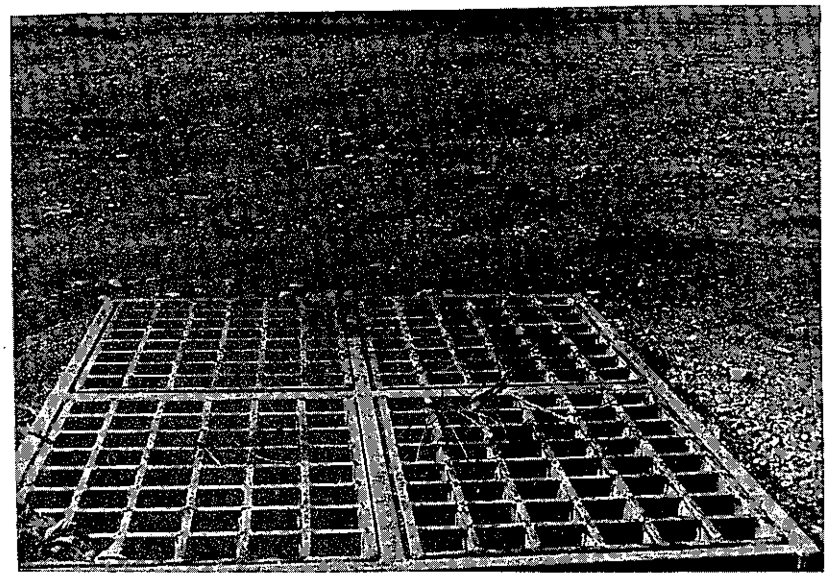


Figure B-7. Grated inlet in unsodded area adjacent to taxiways; no serious erosion around this inlet or on earth slope.

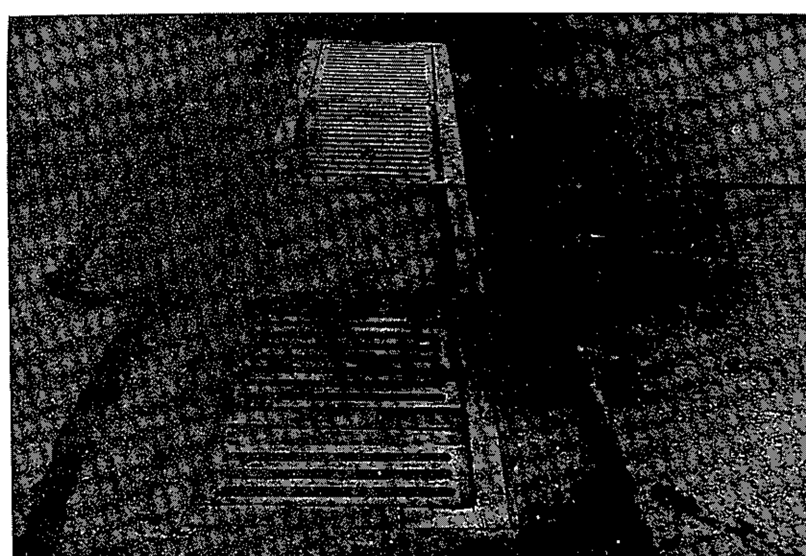


Figure B-8. Large grated inlet in an Operational Apron; has large capacity for water removal; base drainage may be slow here in this low area.

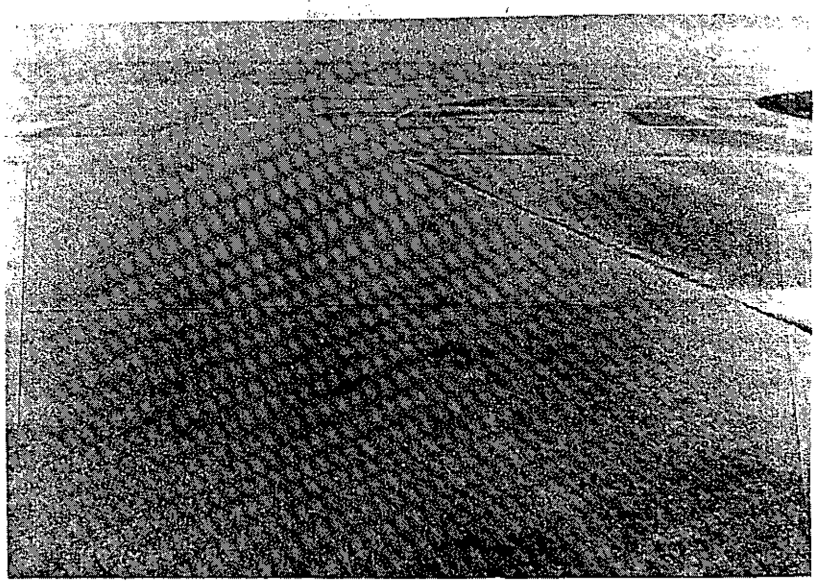


Figure B-9. Poorly drained area with much water still on pavement several hours after a rain.

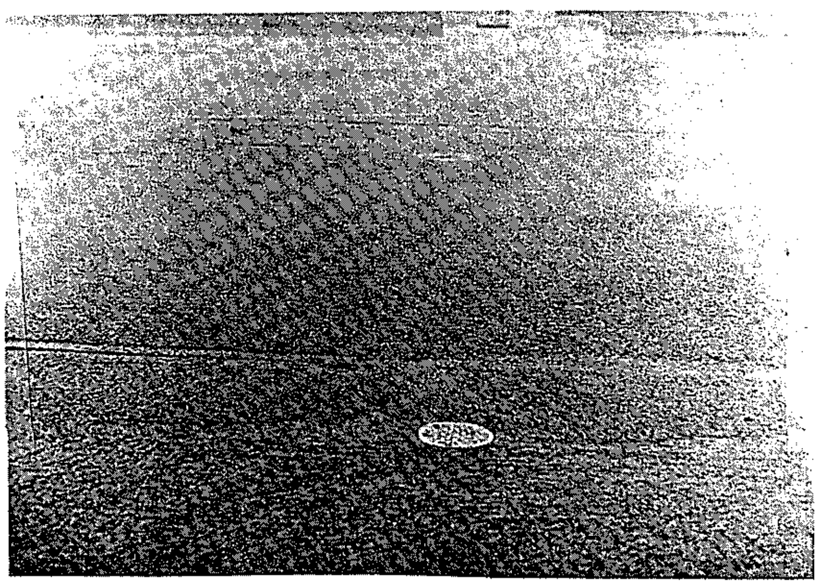


Figure B-10. Another poorly drained area where water collects during every rain; picture taken during a rain.

Joint Sealing and Repair Methods and Problems. All types of pavements have joints or cracks than can allow large amounts of water to enter structural sections when not completely sealed. Keeping cracks and joints perfectly sealed is virtually impossible; however, continuing efforts are being made at all air bases to keep joints and cracks as well sealed as possible. Pavements expand and contract with changes in temperature, which causes compression and expansion of the openings, tending to force joint fillers out of openings and leaving open cracks into which water can enter. Likewise, any physical movement of slabs up and down under traffic causes additional movements tending to loosen joint fillers and enlarge openings. In addition, spalling along joints and cracks in PCC and AC types of pavements, and "D" cracking and blow-ups, often combine to put large amounts of debris on pavements, which create serious hazards to jet aircraft.

Little factual data have been collected in the past on actual inflows of water into pavements through cracks and joints; however, one airfield investigated has a comprehensive underdrain system with many miles of pipes, and outlets discharging from the outlet pipes within the first hour after the beginning of a rainstorm. Typical outflow data are given in Appendix F.

Some of the joint sealing and repair problems seen during the Site Inspection phase of this project are illustrated by photos in Figures B-11 through B-16, on the next three pages.

Figure B-11. A main runway; unsealed crack in 16-in. thick PCC pavement.

Figure B-12. Open, routed crack in an aircraft apron.

Figure B-13. Main runway; open cross joint with some spalling.

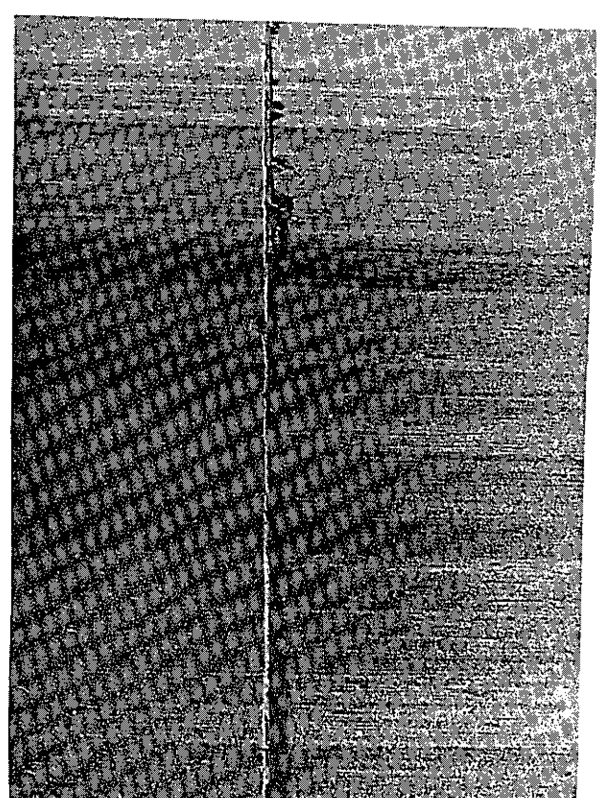


Figure B-14. A primary runway; cross view of an open joint.

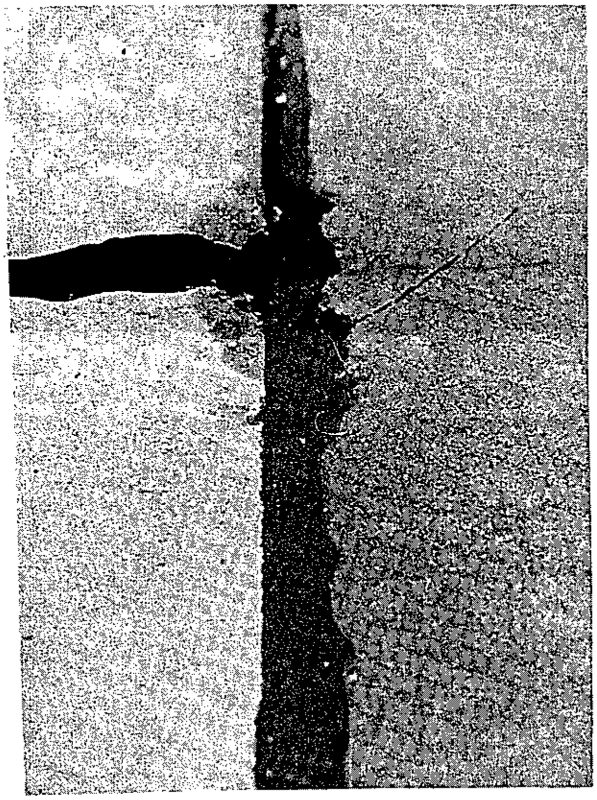


Figure B-15. Typical open joint in a 16-in. thick PCC pavement with preformed joint sealer and poured filler.

Figure B-16. Main runway; epoxy patch is breaking out; saw cut was very shallow (knife blade has dark stain at end which shows depth of saw cut to be about 1/3 inch).

Structural Damages or Weaknesses Associated with Excess Water. Wheel impacts on pavement structural sections containing free water can cause several kinds of deteriorating actions that reduce pavement support and result in structural damage. Among the damaging actions caused or increased by free water are the physical erosion of subbase or subgrade materials out from under pavements; pulsating excess pore pressures in subgrades and bases; increased deflections and stresses in pavement layers, causing deterioration of pavement layers; increased joint damage; and frost action in layers containing excess or free water. Although many of these actions cannot be seen, the results can be seen by the condition of the pavements that are being damaged.

A few photos illustrating some deteriorated pavement conditions that are at least partially attributed to excess water in structural sections are given in Figures B-17 through B-20 on the following two pages. Figure B-17 shows wide cracking of an AC pavement that is probably an indication of subgrade overloading. The severe spalling in Figure B-18 is felt to be initiated by the presence of water. The extensive joint damage and repairing of the pavements in Fig. B-19 are considered to be the consequence of heavy loads and excess water, while the breaking up of the pavement in Fig. B-20 is believed due to frost action aided by liberal amounts of free water held in the structural section by slow drainage.

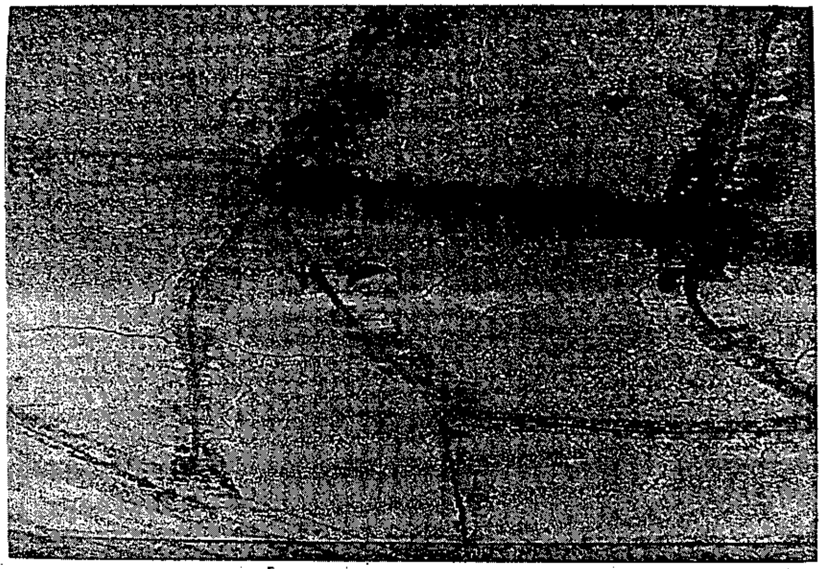


Figure B-17. A taxiway in a moderately heavy traffic area; wide cracks in AC have not yet been covered with a slurry seal.

Figure B-18. A main runway; spalled area, about 18-in. wide at maximum; has been patched with AC; may have started as a joint problem, but is big enough to be of structural importance.

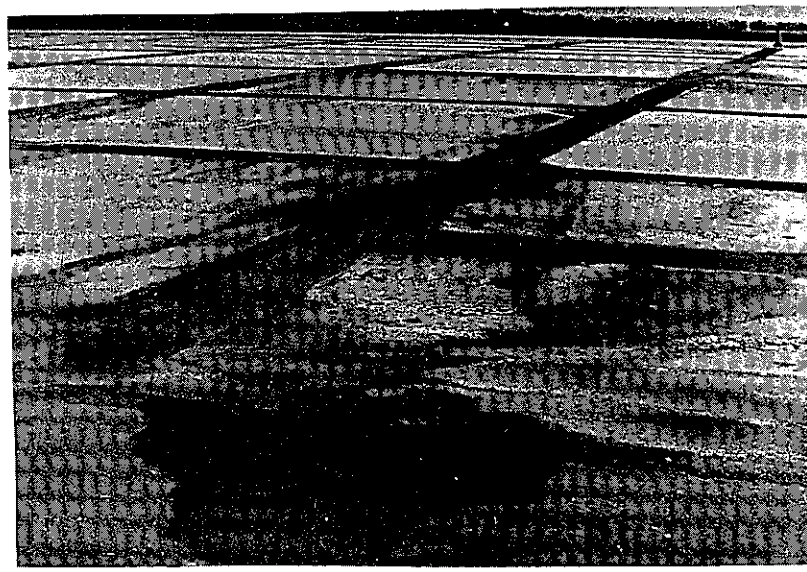


Figure B-19. Extensive damage of pavements; repair of joints has been required; much excess water and bleeding; free water coming out several days after a rain.

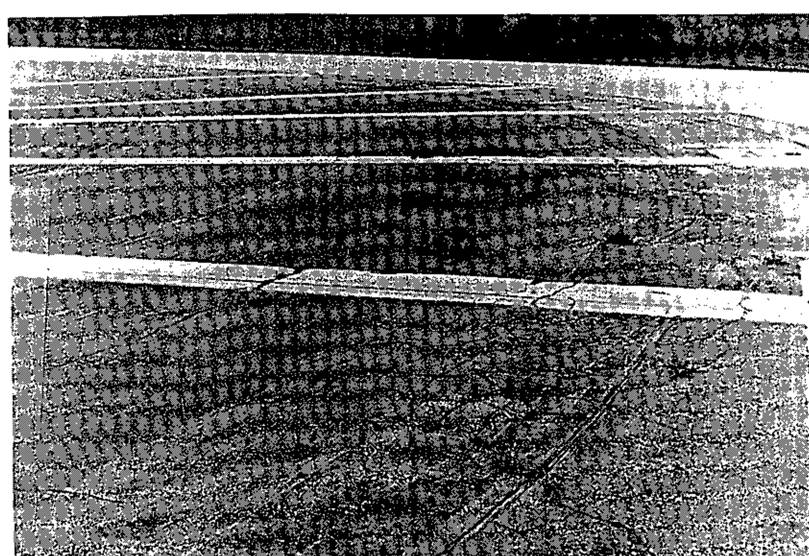


Figure B-20. Severe cracking of thin AC pavement in shoulder of a taxiway; believed due to frost action with liberal supply of water available.

"D" Cracking and Spalling Problems. The well known phenomenon of "D" cracking is one of major proportions in regions of our country where conditions combine to encourage this form of deterioration. It occurs in areas having poor aggregates and large exposure to water and freezing weather. The blow-up problem also occurs in many of these same areas, and causes much roughness to pavements before the actual blow-ups occur. They require extensive repair measures. These problems are most severe in areas where pavements are exposed to large amounts of free water within the structural section. Both of these phenomena put debris on pavements, which is a serious problem to jet aircraft when the loosened materials become sucked into engines.

The spalling of PCC pavements at joints and cracks is another widespread problem, requiring constant maintenance to remove debris and patch the spalled areas.

Several photos taken during the site inspection part of the project which illustrate "D" cracking and spalling at pavement joints are given in Figures B-21 through B-24, on the next two pages. As with all other photos in this appendix, the captions describe the conditions represented by each figure.

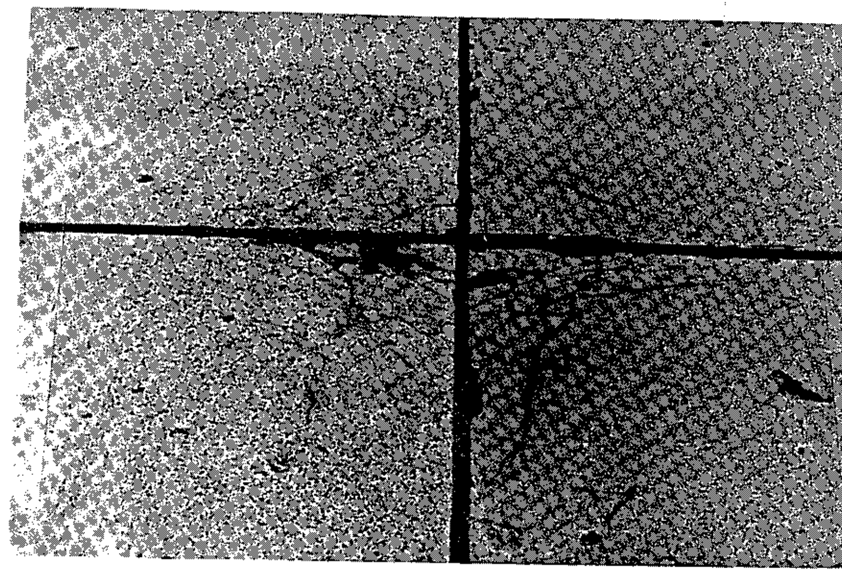


Figure B-21. Taxiway; typical corner "D" cracking in thick PCC pavement; 24"-27" section.

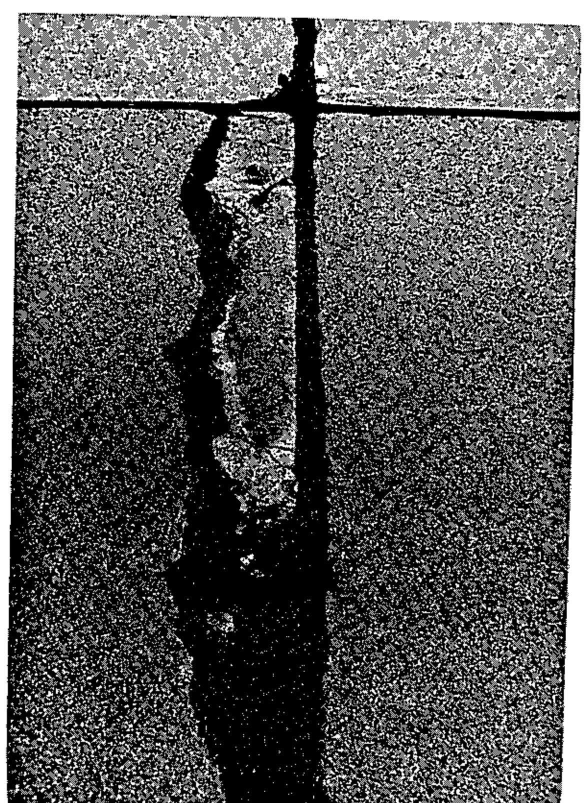


Figure B-22. Operational apron; repaired spall is breaking out; 11-in. PCC on 6-in. PCC and base course.

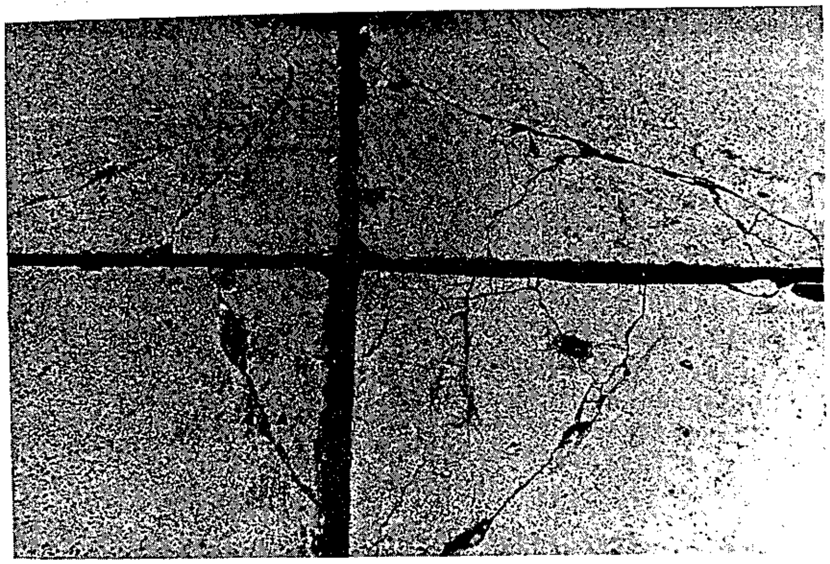


Figure B-23. Taxiway; "D" cracking at intersecting joints in heavy duty PCC pavement.

Figure B-24. Apron extension; deteriorated joints have been diamond-sawed and chipped, as part of joint repair and overlay contract.

Bleeding, Surging, and Other Signs of Excess Water. A number of physical factors compound the problems of draining the wide, flat areas of airfield taxiways, runways, and aprons. Larged cracked surface areas let water in under large downward hydraulic gradients, but only small areas and small lateral hydraulic gradients in aggregate bases are available to drain the water out. As a result, many airfield pavement structural sections contain excess water for many months each year, and during the time free water is there the damages to pavements are greatly increased. When high quality, impermeable paving materials are used, their surfaces generally would need to have open joints or be cracked and deteriorated in order to be more permeable than the aggregate bases. An exception would be the porous AC mixes that are sometimes used.

When free water continues to bleed out of pavements or is pumped out under traffic for many days or weeks, or even months after it stops raining, this is evidence that trapped water is there for extensive periods of time. Grass growing in cracks or joints of pavements is also evidence of a plentiful water supply.

Photos in Figures B-25 through B-28 illustrate some of the conditions seen in the site inspections at the various airfields included in this study (on two following pages), and are evidence of the entrapment of water in structural sections.

Figure B-25. Warm-up apron near the end of a runway; dark stains indicate possible surging area (water squeezed out by planes); warm-up apron at end of runway at taxiway.

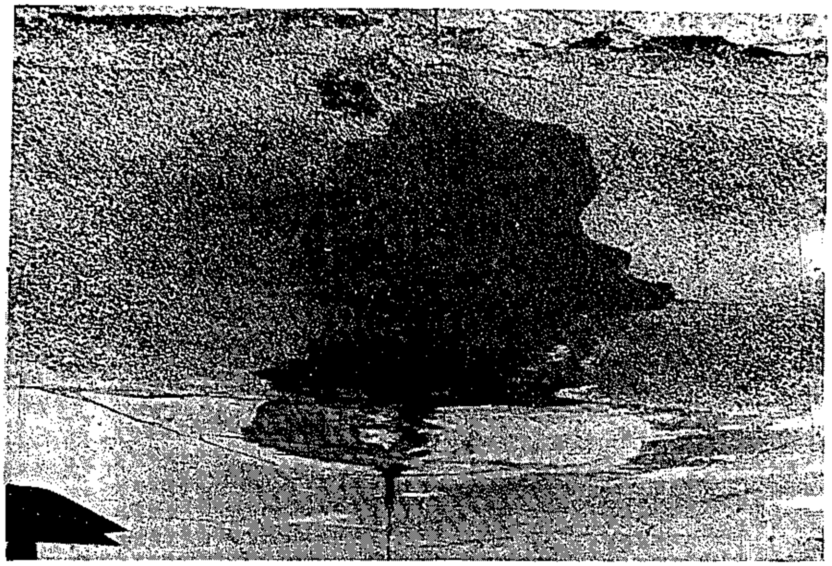


Figure B-26. Old runway, bad bleeding, much pavement damage from excess water.

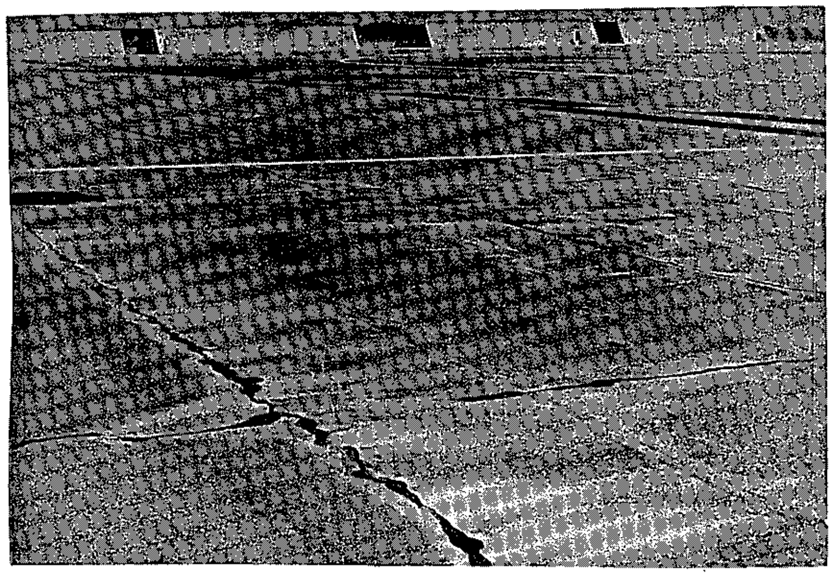


Figure B-27. Parking apron; excessive bleeding shows here; much patch work and joint repairing has been required.

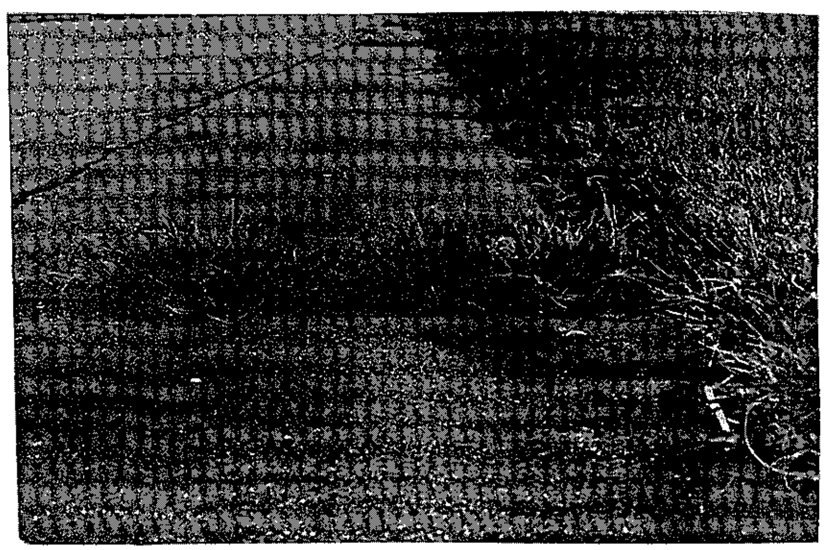


Figure B-28. Taxiway; high sod along edge; this is in a "bathtub" condition; profuse grass in cracks in AC is indication of plentiful water supply; a very common condition.

Entrapment of Water on Bases or Subgrades. Some of the preceding photos show outward signs that free water is trapped within structural sections. Indications of the way water remains in bases or subgrades can sometimes be seen after they have been rained on during construction.

During the site inspections, the writer visited two airfields having construction underway, where bases or subgrades had been rained on a few days before the visit. In both cases, water was still standing in these construction areas during the visits. The way water can stay on base courses (as seen in the photos in Figures B-29 and B-30, on the following page) is an indication of the kind of drainage that can be expected after the balance of the structural section is completed in such areas.

Figure B-29. Taxiway; dug out portion showing water is still standing on base in trench several days after light rain.

Figure B-30. Taxiway; another view showing wet spots on base course several days after a rain.

Reflection Cracking Through Overlays. When pavements begin to show structural damage, or the load-carrying capacity of pavements needs to be increased, overlays of asphaltic materials, tar-rubber, or PCC, are often placed. The overlays provide increased total thickness of structural section, can correct for losses in grade, and hopefully, will reduce infiltration of water into the structural section.

Overlays can often be of great benefit to an airfield, particularly if they are of substantial thickness. Very often, thin overlays (three or four inches, or less) do not provide much structural benefit. In addition, reflection cracks often show up within a year or so after placing, and allow surface water to enter almost as freely as before they are applied.

The photos in Figures B-31 through B-34, on the next two pages, illustrate the manner in which reflection cracks often develop in overlays of AC or tar-rubber.

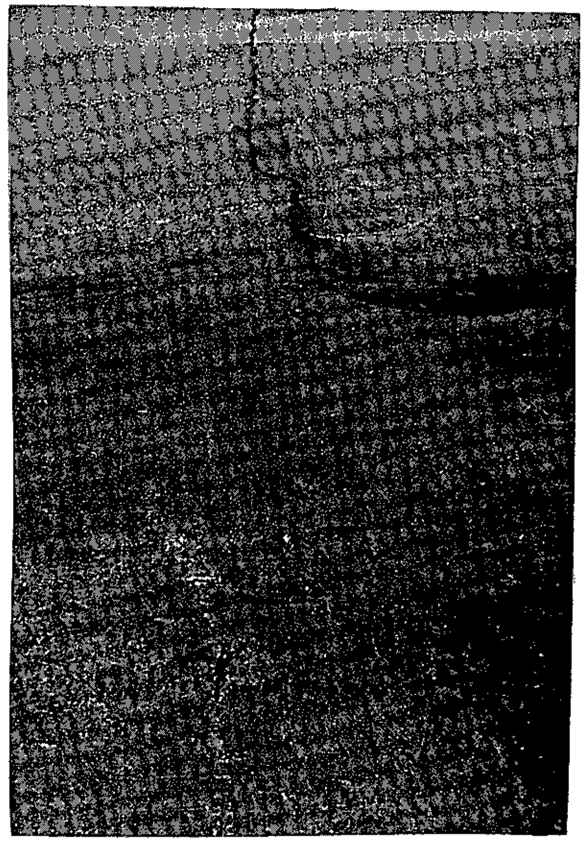


Figure B-31. Parking apron; reflection cracks in 2-in. tar-rubber overlay on 16-in. PCC.

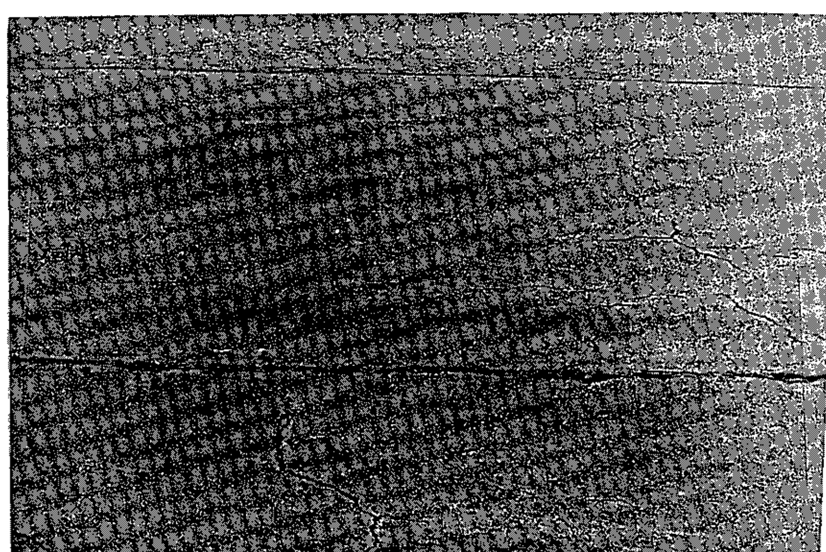


Figure B-32. Parking apron; reflection cracking in 7-in. AC overlay on 8-in. PCC.

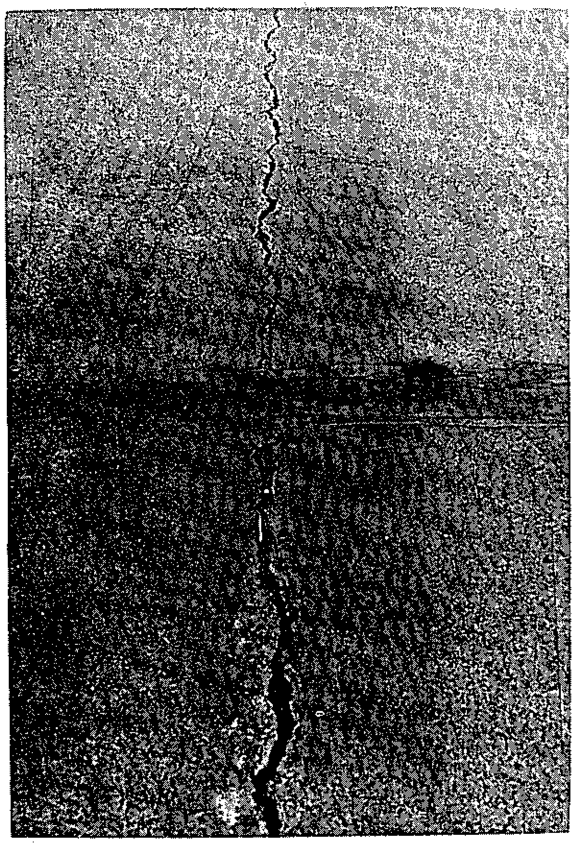


Figure B-33. Parking apron; cracks coming through tar-rubber overlay.

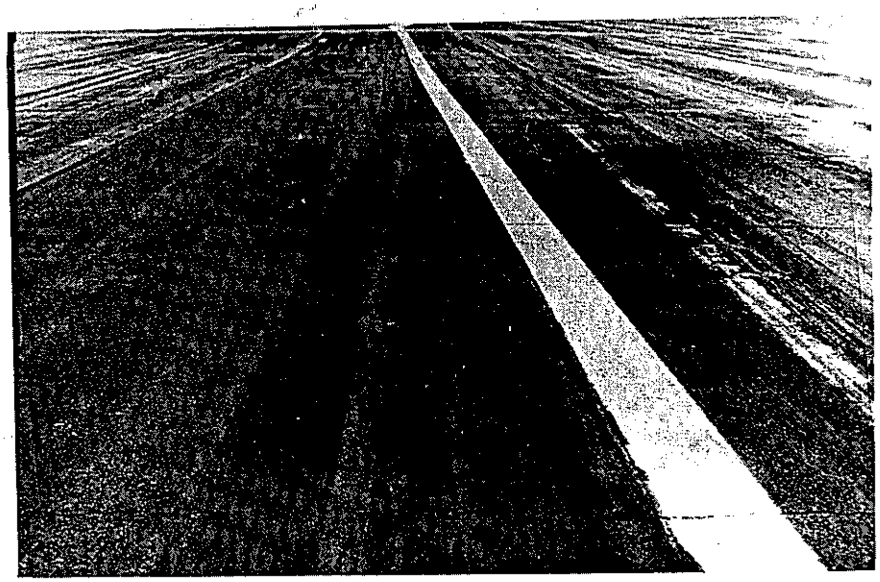


Figure B-34. Extensive reflection cracking in 2-1/2 inch AC overlay on PCC pavement.

APPENDIX C

Field Investigations - Airfield A

CONTENTS

FIGURES

1 GENERAL INFORMATION

Between 1957 and 1959, a 300-ft wide by 12,000-ft long runway, 350,000 sq yds of accessory aprons, and 21,000 feet of 75-ft wide taxiways were constructed for this facility. In a semi-arid climate with generally mild winters and hot summers, the average annual precipitation is about 18 inches, ranging from a trace in July and August to 3.8 inches in December (see Fig. C-18). Snowfall averages about 0.2 in. per year. Frost occurs infrequently and does not penetrate to any noticeable depth below the ground surface. The subgrade soils are generally low plasticity clays of the CL classification, with alternating layers of clay, clay gravel, sand, and gravel. Some sandy silt and some conglomerate are also found. Natural subgrade drainage is relatively slow, although the water table is fairly deep.

The field has had a variety of types of planes since its construction, including over 50,000 cycles of B-52 landings and takeoffs. Its heavy-strength pavements have had no serious maintenance problems, although engineers at the facility have noted surging and bleeding of pavements at a number of locations, and expressed the belief that heavy wheel loads may be causing some detrimental actions associated with excess water within the structural section. Rather substantial patching of joints in portions of the heavily used taxiways has been required.

On September 21, 1972 an initial visit was made for discussions and inspections of drainage conditions at the base. A field inspection of pertinent pavements on the runway, taxiway, and some large apron areas was then made in the company of an officer from Operations. The base engineers explained that at times perched water collects in and under some of the pavements, particularly at lower slow draining areas. Under the weight of heavy plane wheels, water bubbles have been seen coming up from joints in the heavy-duty pavements, and it has been thought that the rocking of slabs under moving loads has been detected. Although there is no evident structural damage, some of the engineers feel that the excess water that gets trapped in the pavements and bases is causing some erosion of the bases and some loss of support of the pavements. They feel that this may be shortening the useful life cycle of some of the pavements.

There are a number of locations on aprons, taxiways, and the junctions between taxiways and the runway where water tends to collect on the pavements during heavy rains, and does not drain off as fast as would be dedired (see Figures C-14, C-15, and C-17). At a number of locations, stains near joints indicate that surging or pumping may be taking place under heavy planes, as already noted (see Fig. C-5).

Except for the localized areas mentioned, surface drainage is generally good. Largely surface waters flow into ditches from which they are fed into natural drainage ditches. Typical conditions, and close-ups of observation wells installed under this project are illustrated in Figures C-2 to C-5, and C-14 and C-17.

2 INSTALLATION OF OBSERVATION WELLS

After discussing the objectives of this study with the airfield engineers and with CERL's Project Manager, this airfield was selected as one of the sites for more detailed investigations. A number of small-diameter pipe observation wells were drilled and installed at selected locations in taxiways at this air base. Because of traffic volume for the base, it was not possible to shut down and occupy the runway for the time needed for installation of one or more wells. Consequently, wells were put in at other locations where it was felt that useful information would be obtained (see Fig. C-1). Altogether, seven wells were put in.

Using a Failing Drill Rig, holes were diamond drilled through the PCC pavement at selected locations. Chopping bits were used to make holes in the AC shoulders (see Figures C-2 and C-3). All holes were deepened in base, subbase, or subgrade with a split-spoon sampling tool or an auger. In a 10-hour day, the seven wells shown as Wells 1 to 7 on Fig. C-1 were installed.

Wells were put in by the following procedures: (1) a hole approximately 3 inches in diameter was made through the pavement and underlying layers to the desired depth; (2) pea gravel was placed in the bottom of the hole to fill the space between the bottom of the hole and the 1-1/4 in. diameter galvanized water pipe; (3) the pipe was set on the pea gravel, carefully adjusting it vertically in the hole, and centering it in the hole; (4) pea gravel was placed in the annular space around the pipe to within 5 or 6 inches of the top of the pavement; (5) the top of the annular space was then sealed with a fast-setting sand-cement grout, leaving a small cup-shaped space in the pavement (see Figures C-4, C-5, and C-16).

Cross sections through the locations of the wells, and logs of the holes and the wells are shown on Figures C-6, C-7, and C-8.

Early in 1972 the Base Civil Engineer's office had cored through the PCC pavement of the Operational Apron near an area where surging had been noted, and where drainage was particularly poor. After this hole had been cored, water poured out for several weeks. This area is under water for extensive amounts of time during and after rainfalls of any significance. This well is shown as Well 8 on Fig. C-1.

3 IN-PLACE PERMEABILITY TESTS

After Wells 1-7 were completed, in-place permeability tests were made by the writer, with the help of a member of the Base Civil Engineer's staff, either by measuring the rate of fall of the water level, or by estimating a rate of flow sustaining a small head in a well. Subsequently, estimates of the average permeabilities of the materials tested in each well were made by approximate calculations with Darcy's law, using estimated values for the effective hydraulic gradient, and the discharge area.

In making the tests, some pre-saturation was accomplished before rates of fall or flow were measured. Although the tests are somewhat approximate, it is felt they give a measure of the order of magnitude of the permeabilities of the materials tested.

Readings of water levels or estimated inflow quantities during these tests are given in Figures C-9, C-10, C-11, and C-12, together with other information. Estimated coefficients of permeability are also given in these figures, as well as the soundings discussed in Chapter 4, "Soundings in Observation Wells."

Referring to Figures C-9, C-10, C-11, and C-12, it is seen that the tests of the aggregate base under PCC pavements gave permeability values of 0.01, 0.001, and 0.006 cm/sec (32, 3, and 17 ft/day); whereas those made in wells in AC surfaced shoulders ranged from 3×10^{-6} cm/sec (0.01 ft/day) for Well 5 to over 2 cm/sec (6000 ft/day) for Well 7. The general conclusion from these tests is that the base course under the PCC pavements is a moderately permeable, well-graded blend of sand and gravel; whereas the materials under the thin shoulder pavements and bases are native gravels and clay-gravel mixtures, generally low in permeability, but in some places very permeable. The base course under the PCC pavements appears to be sufficiently permeable to allow water to migrate toward lower elevations along the taxiways and under the aprons, where it tends to collect.

Wells 4 and 5, Wells 6 and 7, and Well 8 are all in low areas where both surface and subsurface drainage are poor. There has been substantial joint repairing in low portions of the taxiway system such as at Well 6; and the engineers have thought they detected bubbling of water out of the pavement joints, and rocking of the slabs in traffic areas near Well 8.

4 SOUNDINGS IN OBSERVATION WELLS

Approximately 18 hours after completion of the wells, a check was made of the water levels in the wells, and free water was found in only one well (Well 6, see Fig. C-11). Several times after the initial readings, depths to water and depths to pea gravel in wells were measured, both during and at various intervals of time after rains. All of these readings are summarized in Figures C-9, C-10, C-11, and C-12. It can be seen that during and immediately after significant rainfalls, the water levels frequently rise to or near pavement level, and then lower quite rapidly in some wells, but very slowly in others. It can also be seen that the pea gravel in Well 4 evidently rose about 3 inches between October, 1972 and the middle of January, 1973 (see Fig. C-10). This behavior is considered likely to be the result of large pulsating pore pressures building up under the PCC pavement due to heavy wheel loads moving across the pavement. A similar, but more spectacular movement of the pea gravel backfill occurred in one of the wells at Airfield F (see Appendix E).

It may be seen by referring to Figures C-9 to C-12 that on November 7, after 0.6 inches of rain, all of the new wells had appreciable depths of water, and two were completely full. On November 15 (at 0915 hours), some time after intermittent rains for several days had totalled 2.17 inches, three of the seven wells installed for this study were empty, while the other four, and Well 8 showed varying levels of water. Wells 4 and 8 were completely full and Well 5 was full to within an inch of the top of the pavement. On January 9, 1973, immediately after a heavy rainfall, all of the wells were full, nearly full, or had water over the top of the pavement.

5 DISCUSSION OF THE PAVEMENTS TESTED

East Taxiway - 800 ft South of Taxiway 4. This is a high elevation area on the taxiway system, which was selected because it was higher than most of the East Taxiway, although brown stains suggested the possibility that some kind of drainage problem might exist along this part of the taxiway. Wells 1, 2, and 3 were located here (see Fig. C-1 and Fig. C-6). Soundings in these wells indicate that water does get into the structural section during rains, but that it drains out quite rapidly afterwards (see Fig. C-9 & C-10). Thus, on Nov.7,about 6 hours after a heavy shower, free water was found in all three of these wells within a foot or less of the pavement surface, but at other times, after greater amounts of time for drainage, these wells showed little free water or none at all (see Fig. C-13). The staining at this area appears to be a discoloration due to the slow flow of water off the AC shoulder (on the high side of the taxiway) onto the PCC pavement, with the possibility of slight stripping or disolution of asphalt films from the AC pavement.

Taxiway 3 - 160 ft East of Main Runway. This location was selected because it appeared to have poor surface drainage, and dark stains near some of the joints in the PCC pavement appeared to be signs of possible surging or pumping of water out of the joints under heavy wheel loads. Well 4, in the PCC, and Well 5, in the AC shoulder, were installed at this location (see Fig. C-7). Figure C-14 and Fig. C-15 show water standing on the PCC pavement several days after Wells 4 and 5 were installed. Figure C-16 is a close-up of Well 5, showing that the equilibrium water level was an inch below the top of the pavement on December 19, 1972, about 14 hours after a heavy rain. At this same time, water stood about 1/4 inch deep over the PCC pavement at

Well 4.

Examination of the well readings (see Fig. C-10 and Fig. C-11), indicate that free water collects and remains in the pavements at this location for appreciable amounts of time during and after every significant rainfall. Although the pavement shows no physical distress, it appears that some of the dynamic actions of water under heavy wheel impacts are occurring under the pavements. As already noted, soundings to the top of the pea gravel backfill in the wells indicate that as of January, 1973, the pea gravel in Well 4 had risen about 3 inches since its installation (see Fig. C-10).

East Taxiway - 1200 ft. North of Taxiway 4. This location was selected because it is low-lying, and rather extensive repairing of transverse joints with epoxy and asphalt sealers had been required in this area. It appeared that there may have been some working of slabs under heavy wheel loads. Well 6 is in the PCC at this location, and Well 7 is in the West AC shoulder (see Fig. C-8). Every sounding that has been made has shown water in Well 6, with the level rising to the surface or near the surface during or shortly after rains, and lowering to about an inch above the bottom of the 26-inch thick PCC pavement between rainstorms (see Fig. C-11). The in-place permeability tests made here indicated a coefficient of permeability of about 0.006 cm/sec (20 ft/day) under the PCC and about 2 cm/sec (6000 ft/day) in the shoulder (see Figures C-11 and C-12). Water probably drains into low areas such as this one from pavements at higher elevations, which prolongs the exposure to free water. No significant free water was standing on the pavement on December 19, although a number of other areas had appreciable depths of free water standing on large areas of pavement.

Operational Apron - Southern Portion. Many areas of the Operational Apron show signs of pumping and bleeding. In the general vicinity of Well 8, which was installed by the Base Civil Engineer's office early in 1972, surface drainage is very poor, water stands on the pavement during every significant precipitation, and the structural section remains filled with water long amounts of time after it stops raining (see Figures C-12, C-13, and C-17). As already noted, when Well 8 was inspected for this project (November, 1972 to January, 1973) it was found to be completely filled with water. On December 19, about 14 hours after a rainfall of 0.93 inches, water was about 1/2 inch deep on the pavement at this well, with a noticeable surface flow velocity in the westward direction. At several other times during the period of the observations, water was also on the surface up to about this same depth.

6 DISCUSSION OF DRAINAGE CONDITIONS

The natural subgrade materials, although varying from gravels to clayey gravels, generally are low in permeability and provide slow vertical drainage of water out of the pavements. The permeabilities of the subgrade beneath the primary pavements are estimated to be in the range of 3×10^{-6} cm/sec (0.01 ft/day) or lower. For a coefficient of permeability of this level it could be expected that free water would remain trapped as "perched water" within lower parts of structural sections at least 20 to 30 days after it stops raining.

Although Airfield A was described in pavement condition survey reports as being in a "semi-arid" climate (and this is one of the reasons it was selected for study), it is estimated that in a normal year, rain showers or storms depositing 0.2 inch or more of water are likely to occur from 20 to 25 times each year, with lesser amounts a number of additional times. Precipitation events that occurred in 1972 are shown in Figure C-18. Except for an extremely dry summer period of about 3-1/2 months, significant rainfalls can occur throughout most of the balance of the year. On the basis of this rainfall record, it is estimated that in areas where water tends to accumulate, pavements may contain free water to varying levels for as much as 240 days in a year. In other areas, particularly those at higher elevations along the taxiway system, free water will tend to drain out of the base course to lower areas. In the better drained areas, it is felt that free water may remain within the structural sections for perhaps 20 to 30 days each year. Major differences between the various areas tested may be noted by examining the typical water profiles in Fig. C-13.

Observation wells put into the pavements at this air base in both "good" and "bad" drainage areas have produced some interesting and useful information about the amount of exposure of various pavements to excess water. If the estimated lengths of exposure that are noted above are reasonable, some of the better drained pavements can be expected to give many more years of trouble-free service than some of the more poorly drained pavements, which are likely to require substantial repairs in the next 5 or 10 years, if heavy traffic volumes continue at this air base.

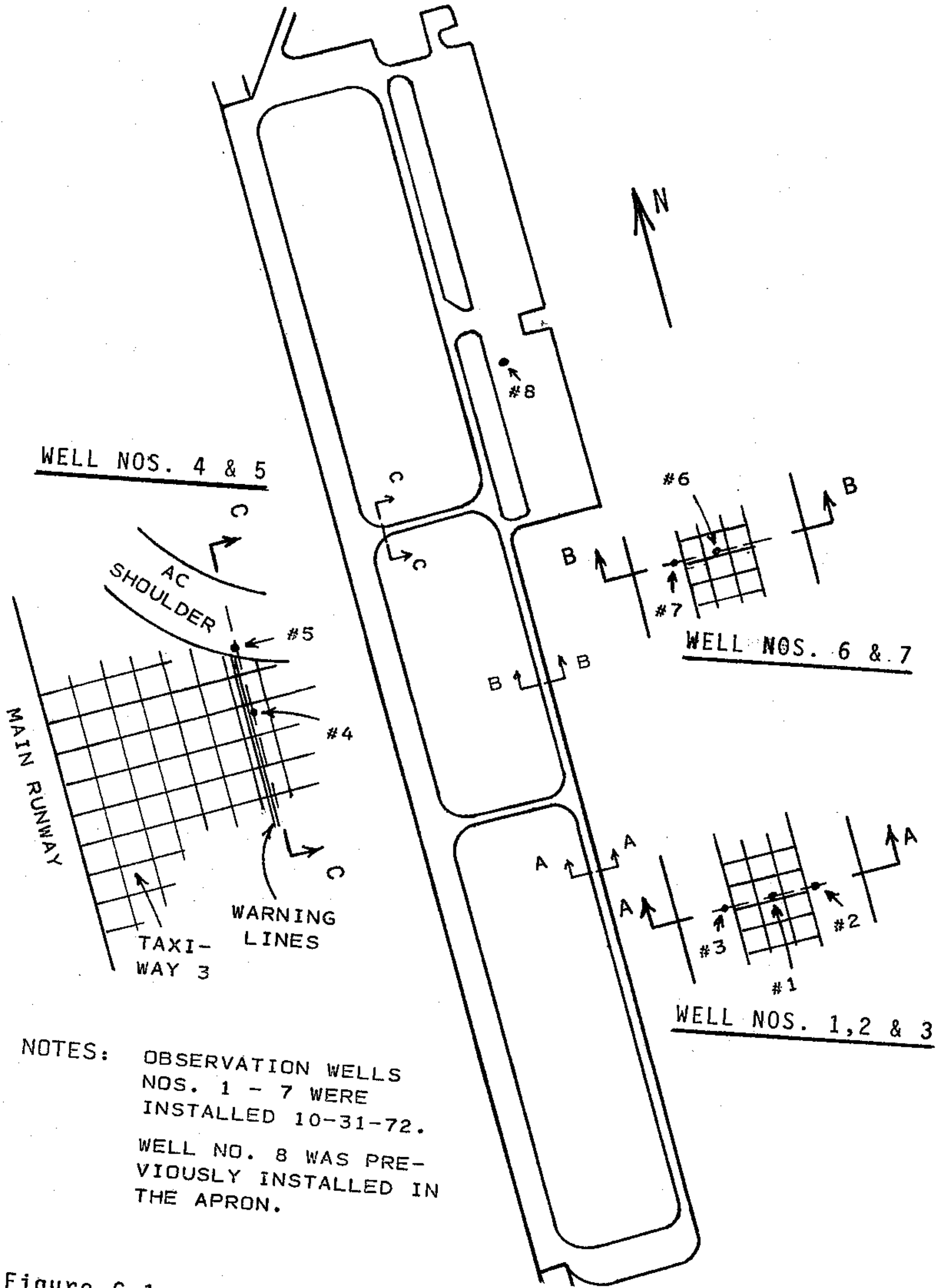


Figure C-1. Locations of observation wells in pavements.

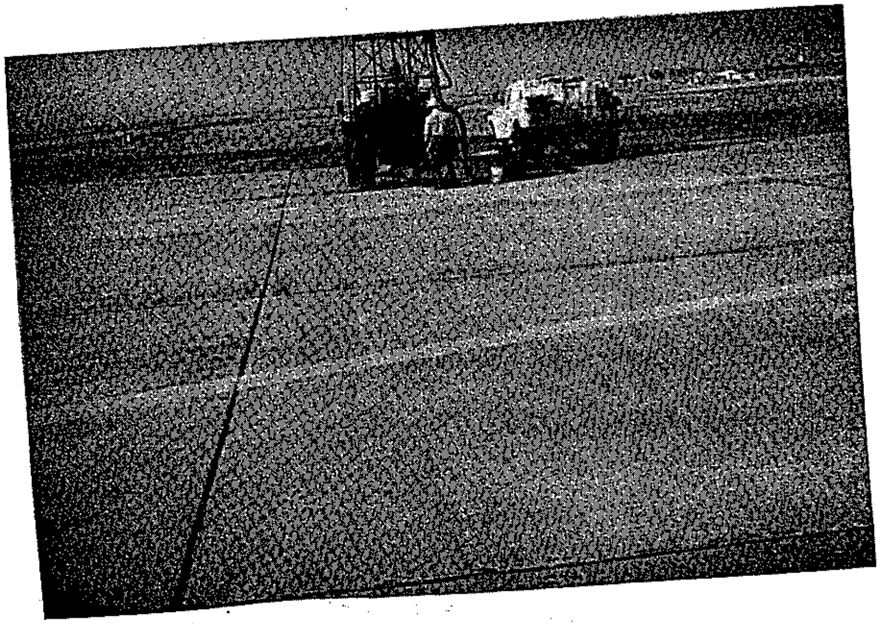


Figure C-2. Drill rig at Well 4; this area has poor surface drainage and very slow subsurface drainage; free water stays in structural section a long time after it stops raining.

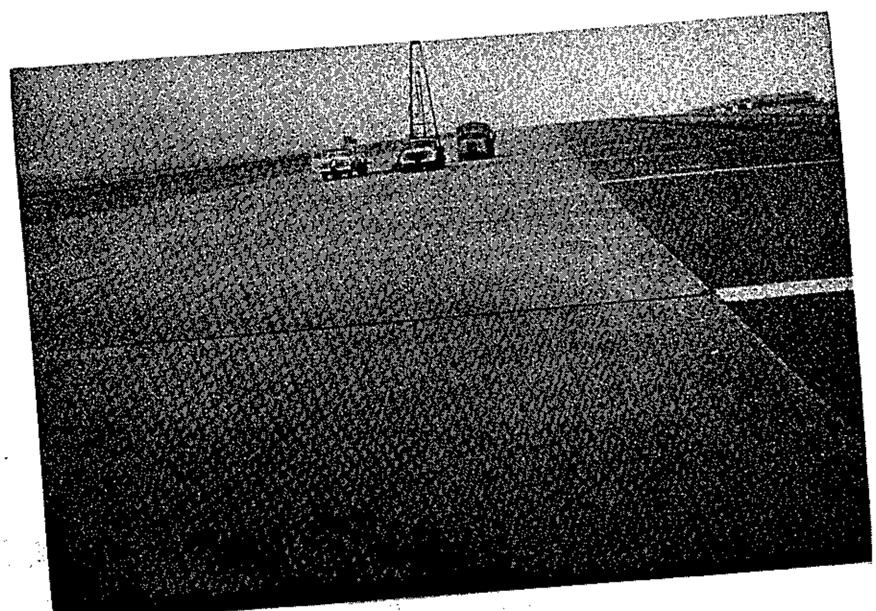


Figure C-3. Drill rig at Well 6; low swale in East Taxiway; water stays in structural section a long time after it stops raining.

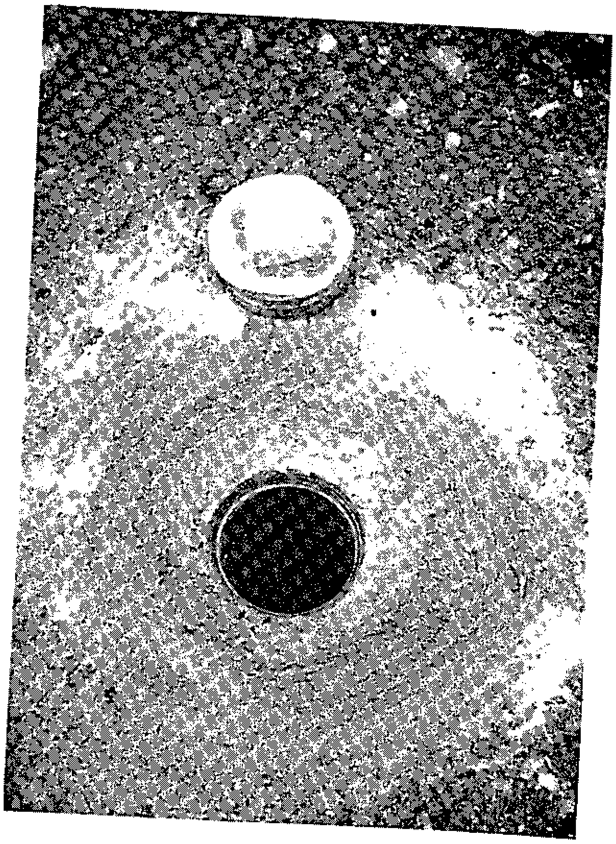


Figure C-4. Shows appearance of a completed observation well; upper part of hole has been sealed with a fast setting sand-cement grout.

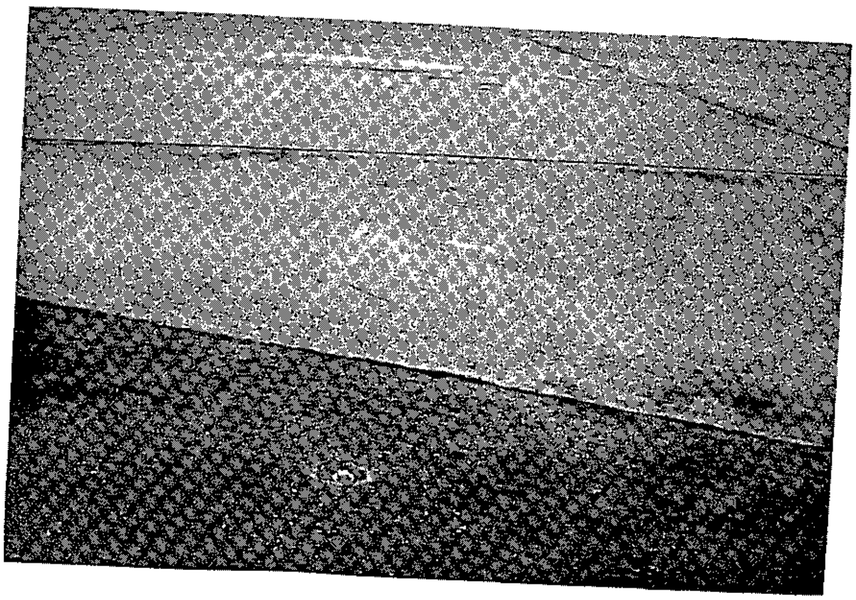
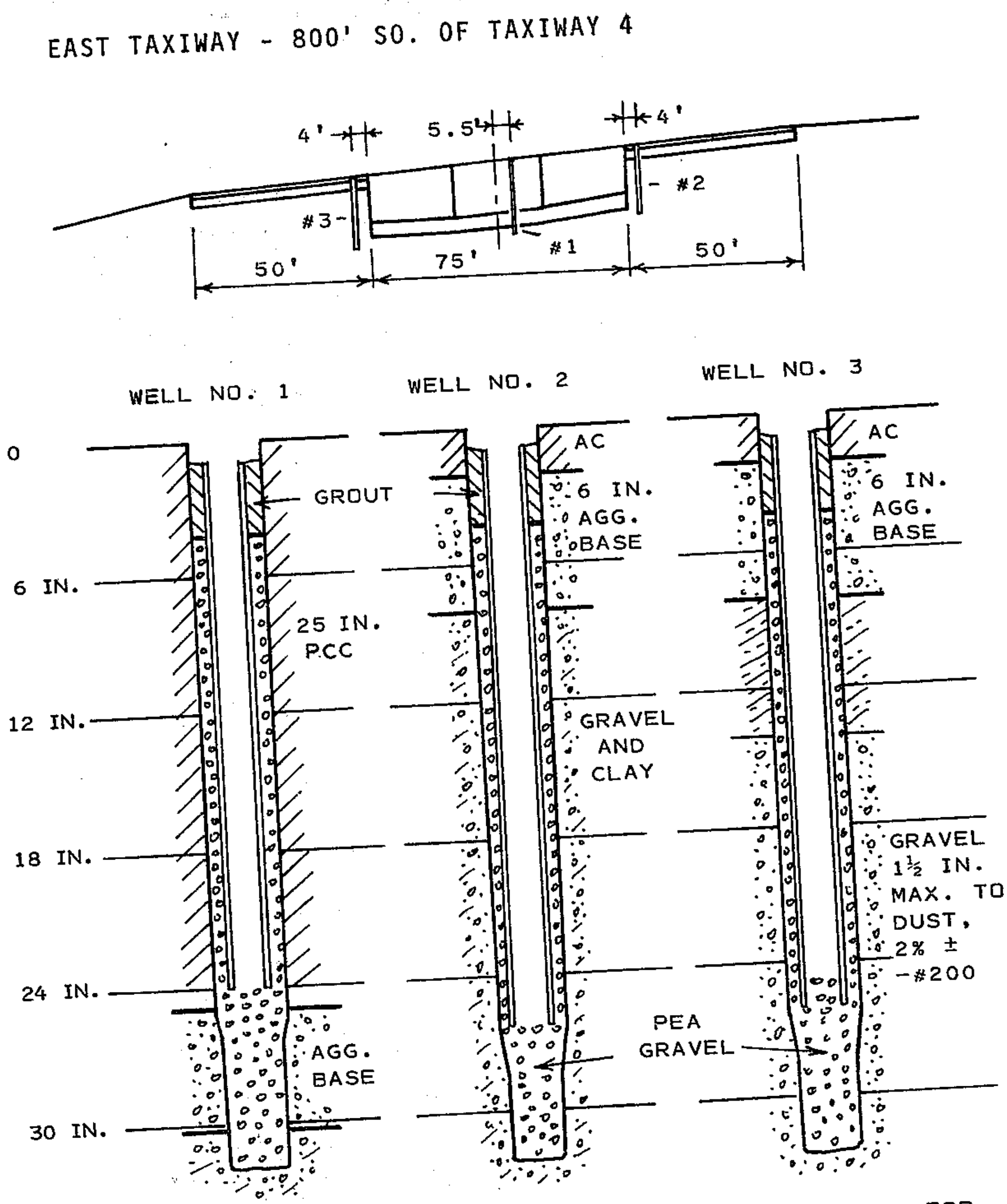


Figure C-5. Cross view of Wells 4 and 5; shows general appearance shortly after installation; Well 4 (near upper center) barely visible; dark stains are signs of surging or bleeding in this area; dry pavement today.



NOTES: HOLES APPROX. 3-IN. DIAMETER; PEA GRAVEL USED FOR BACKFILL; FAST-SETTING SAND-CEMENT GROUT USED FOR SEALING UPPER PARTS OF HOLES AROUND 1¼ IN. GALV. PIPE. VENTED PLUGS IN EXCEPT WHEN TAKING READINGS.

Fig. C-6. Logs of wells 1 to 3.

TAXIWAY 3 - 160' EAST OF MAIN RUNWAY

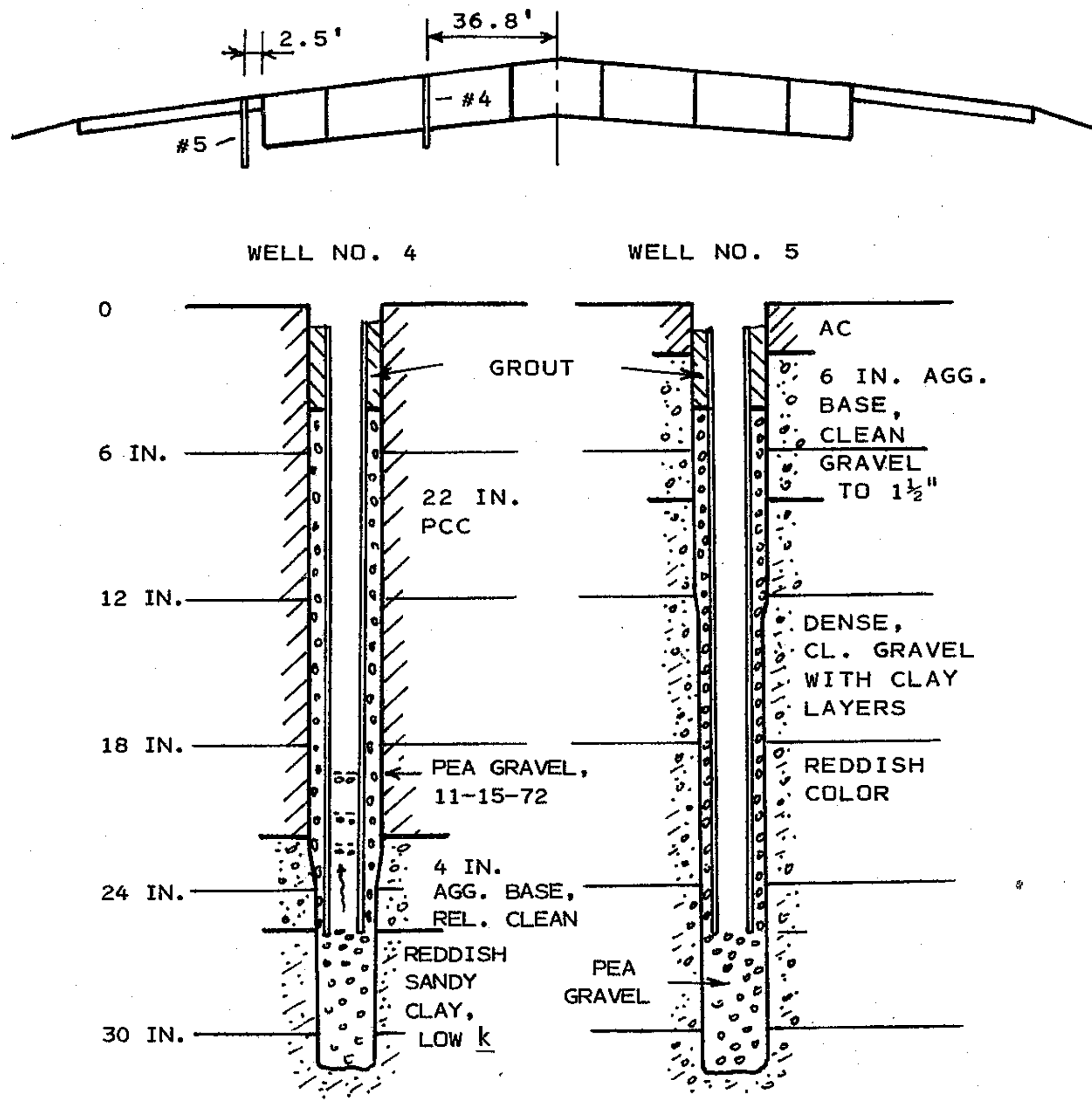
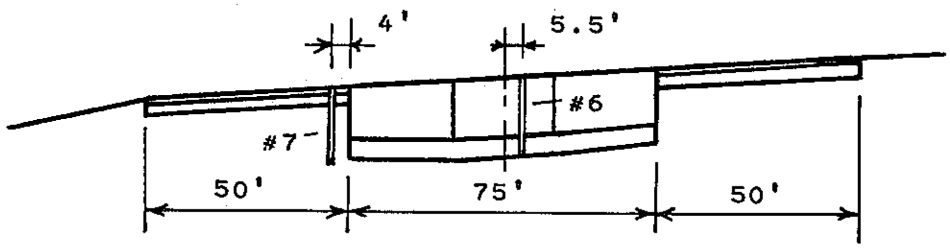


Figure C-7. Logs of wells 4 and 5.

EAST TAXIWAY - 1200' NO. OF TAXIWAY 4



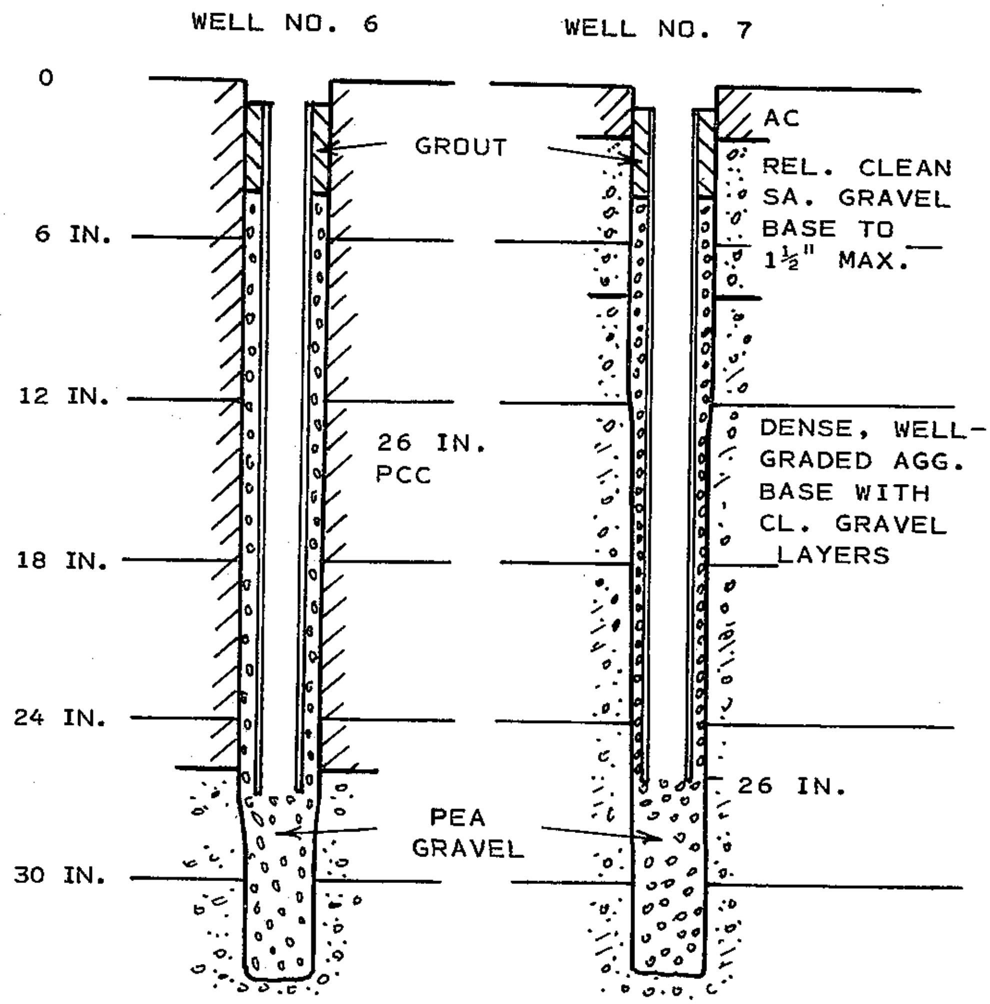


Figure C-8. Logs of wells 6 and 7.

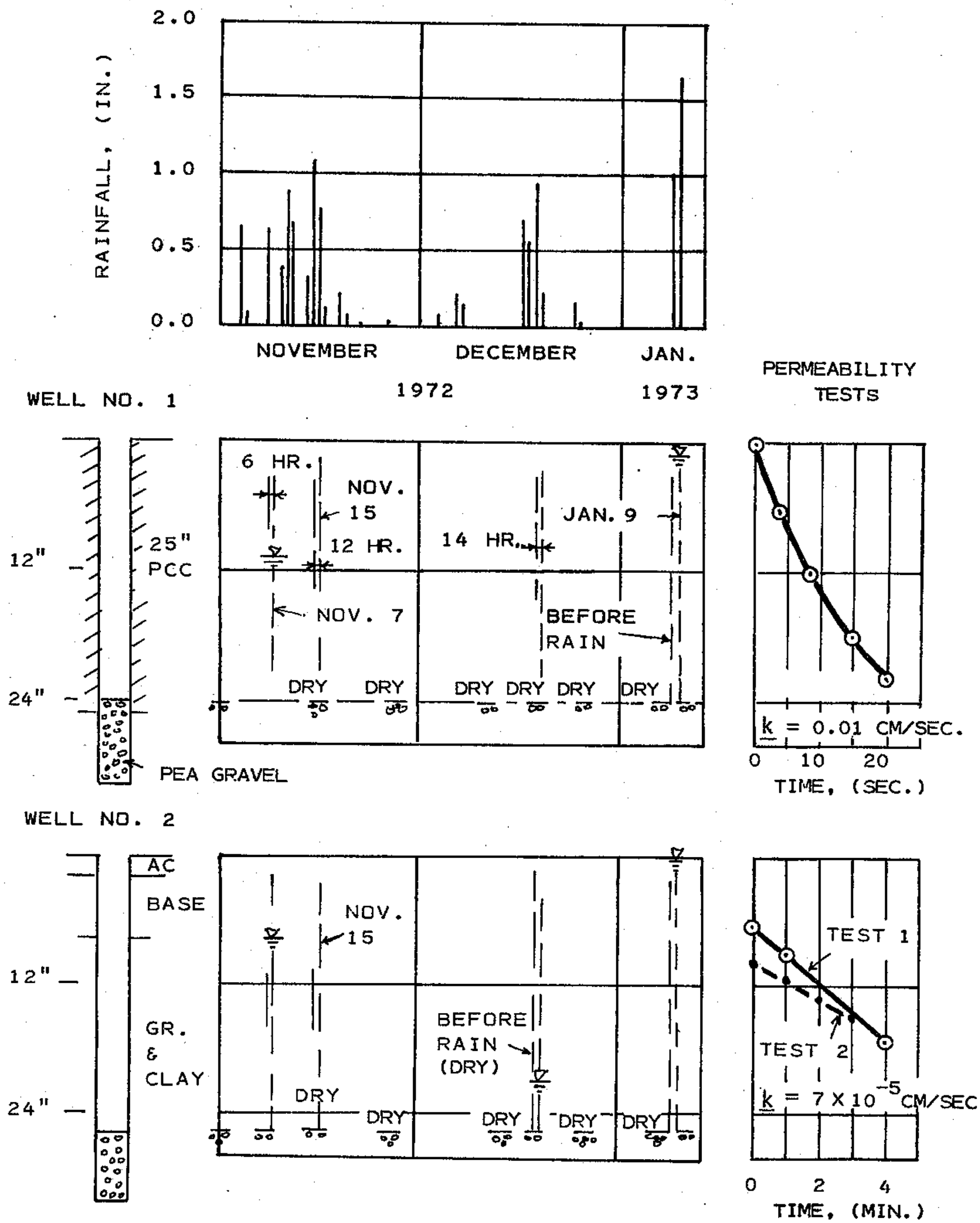


Figure C-9. Field data for wells 1 and 2.

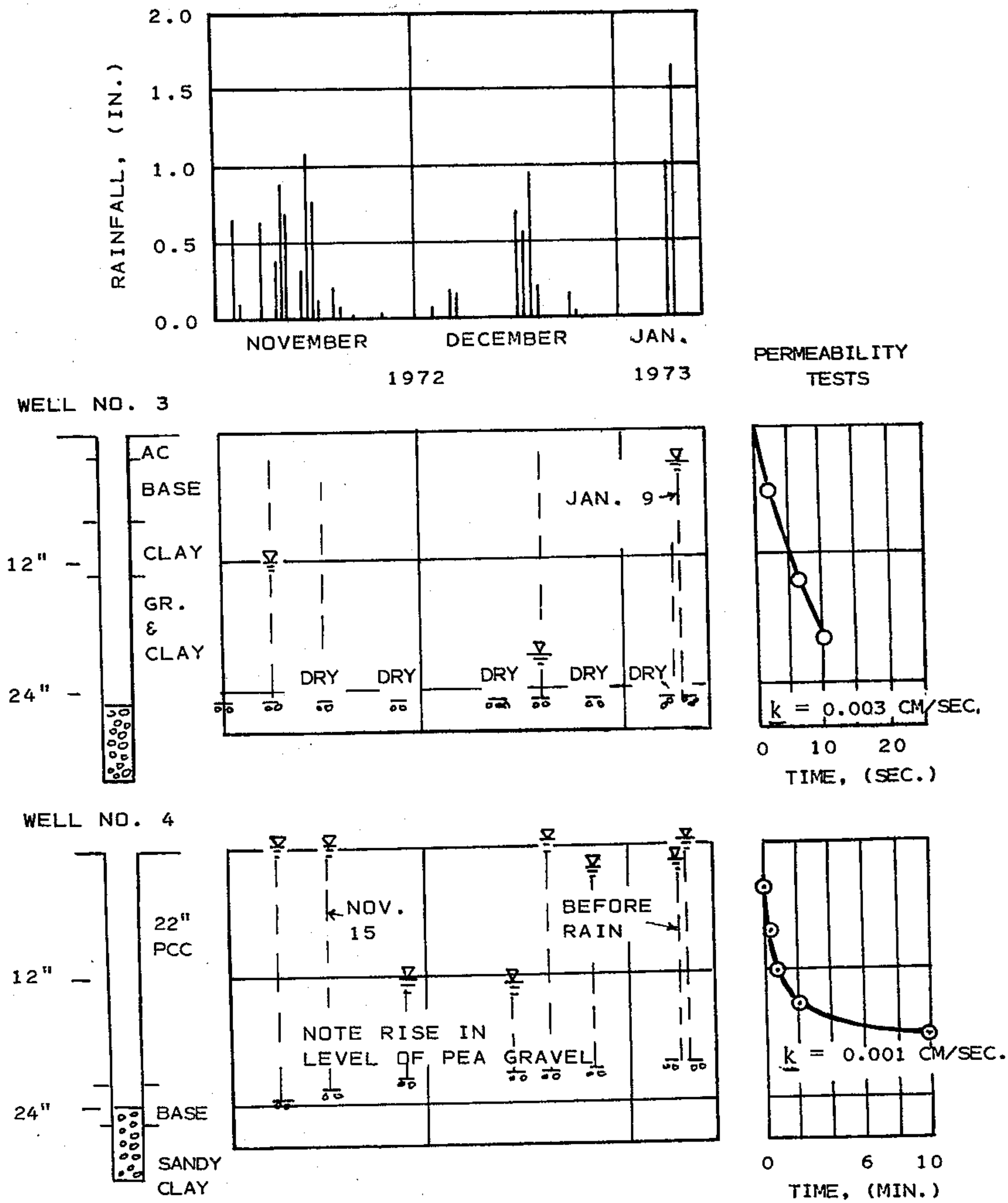


Figure C-10. Field data for wells 3 and 4.

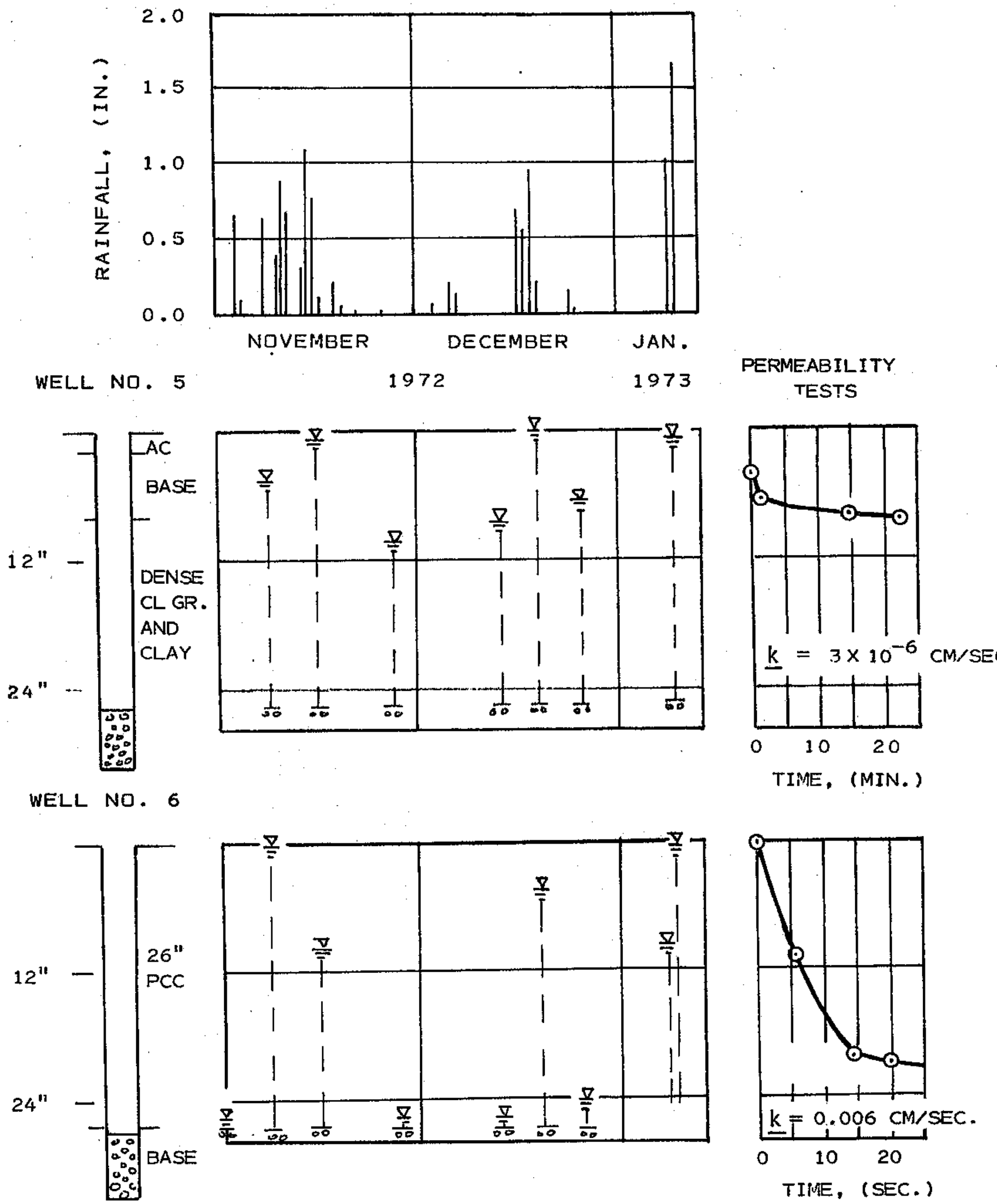


Figure C-11. Field data for wells 5 and 6.

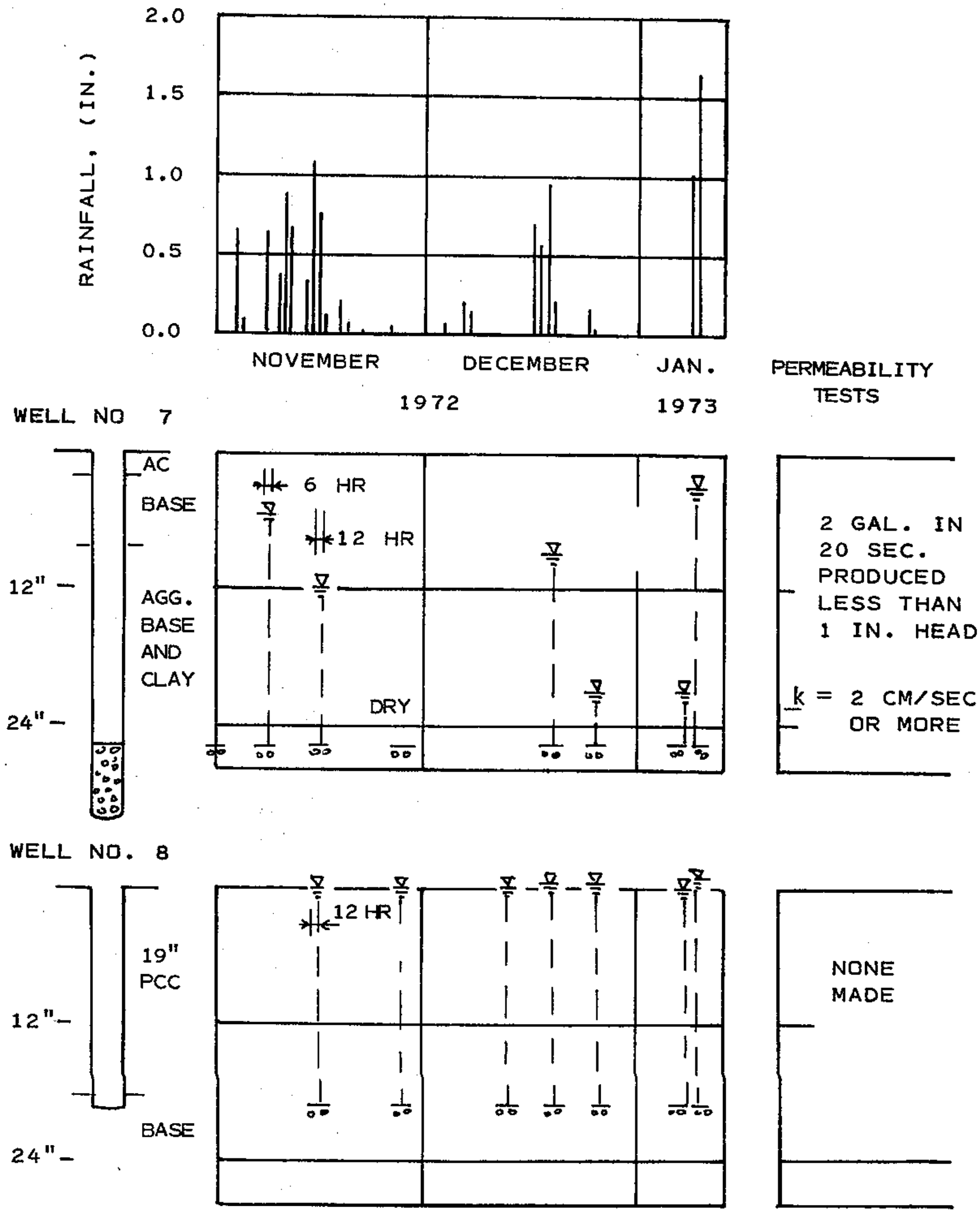
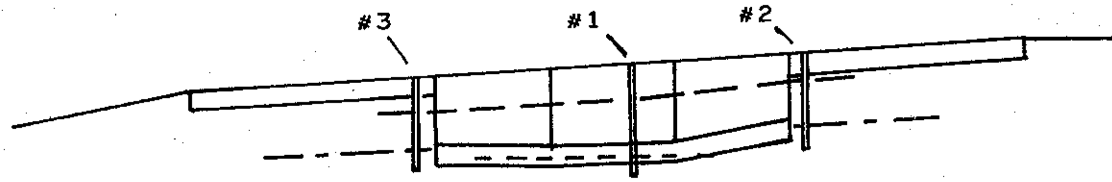
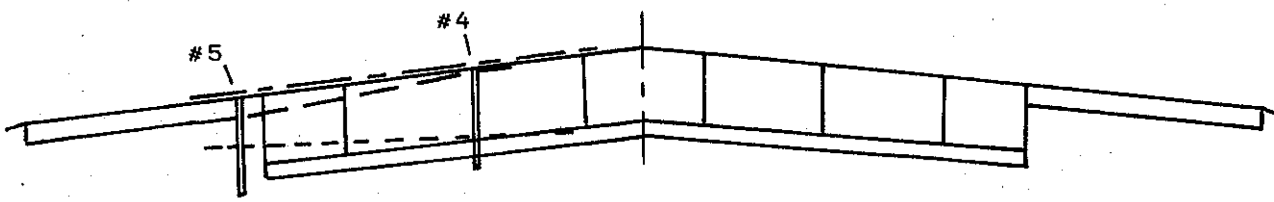


Figure C-12. Field data for wells 7 and 8.

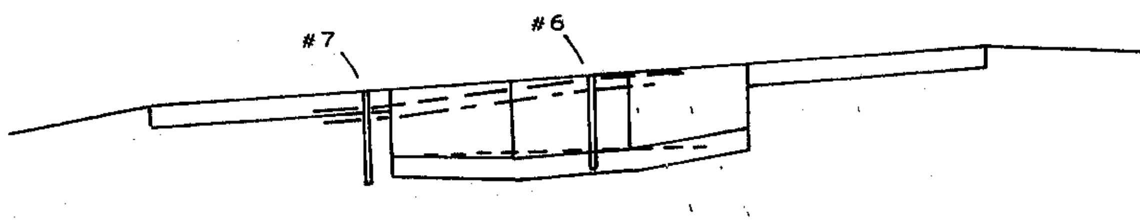
A) EAST TAXIWAY - 800' SO. OF TAXIWAY 4



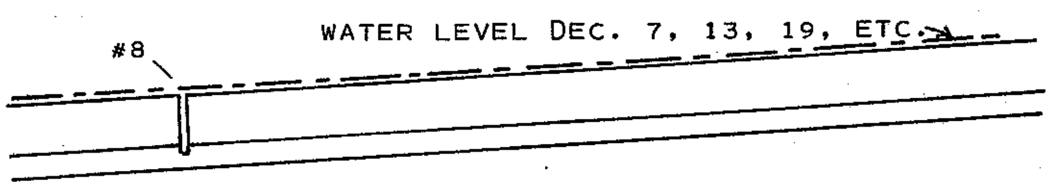
B) TAXIWAY 3 - 160' EAST OF MAIN RUNWAY



C) EAST TAXIWAY - 1200' NORTH OF TAXIWAY 4



D) OPERATIONAL APRON - SOUTHERN PORTION



LEGEND:

TYPICAL WATER LEVELS

— — — — = NOV. 7, 1972

- - - - - - - - = DEC. 13, 1972

— - — - — = DEC. 19, 1972

Figure C-13. Typical water profiles.

Figure C-14. Cross view at Wells 4 and 5 several hours after a rain; shows wet condition; officer is at Well 5.

Figure C-15. View at Well 4, same time as Fig. C-14; about 1/2 in. of water over pavement and well.

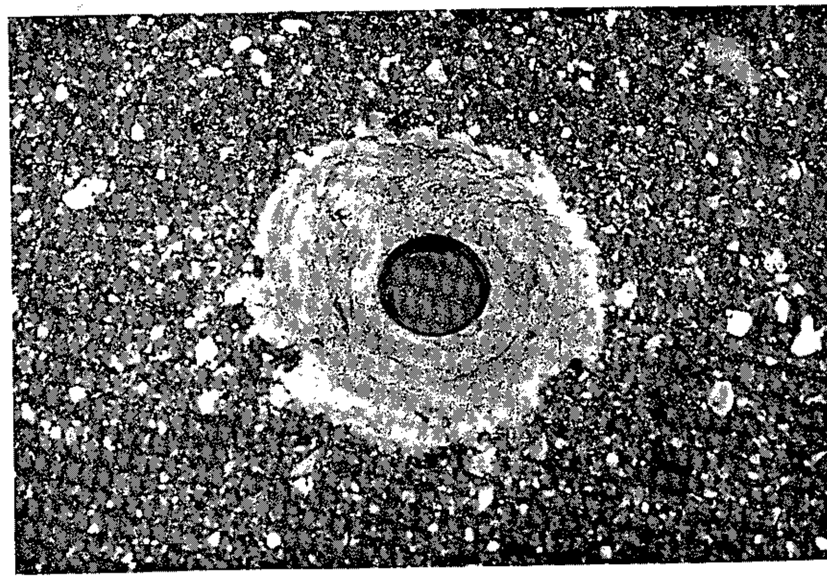


Figure C-16. Close-up of Well 5 several hours after a rain; pavement is damp, but no surface water; hydrostatic head in base raised water to 1 in. from top of pavement.

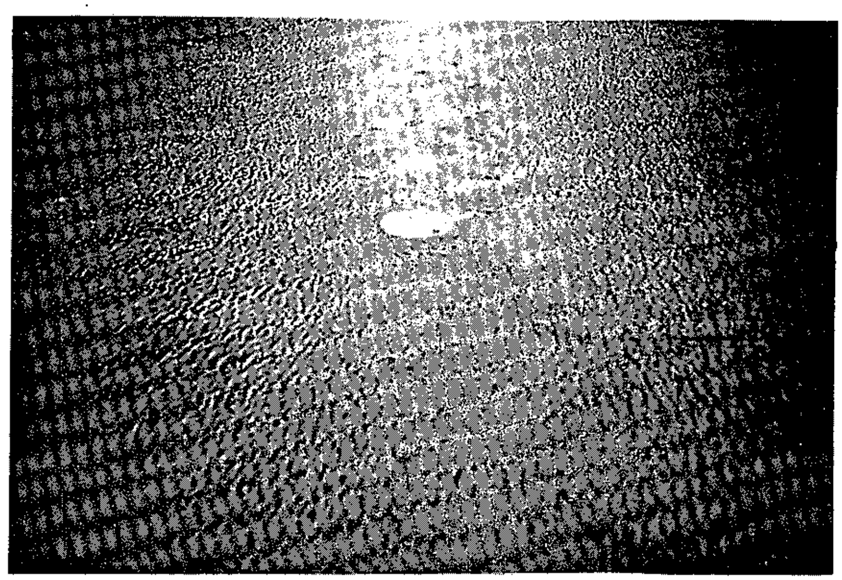


Figure C-17. View at Well 8 during a rain; very poor surface drainage here; much water collects on surface; subsurface drainage also very slow; 1/2 in. of water over surface, strong current; strong light reflection off water.

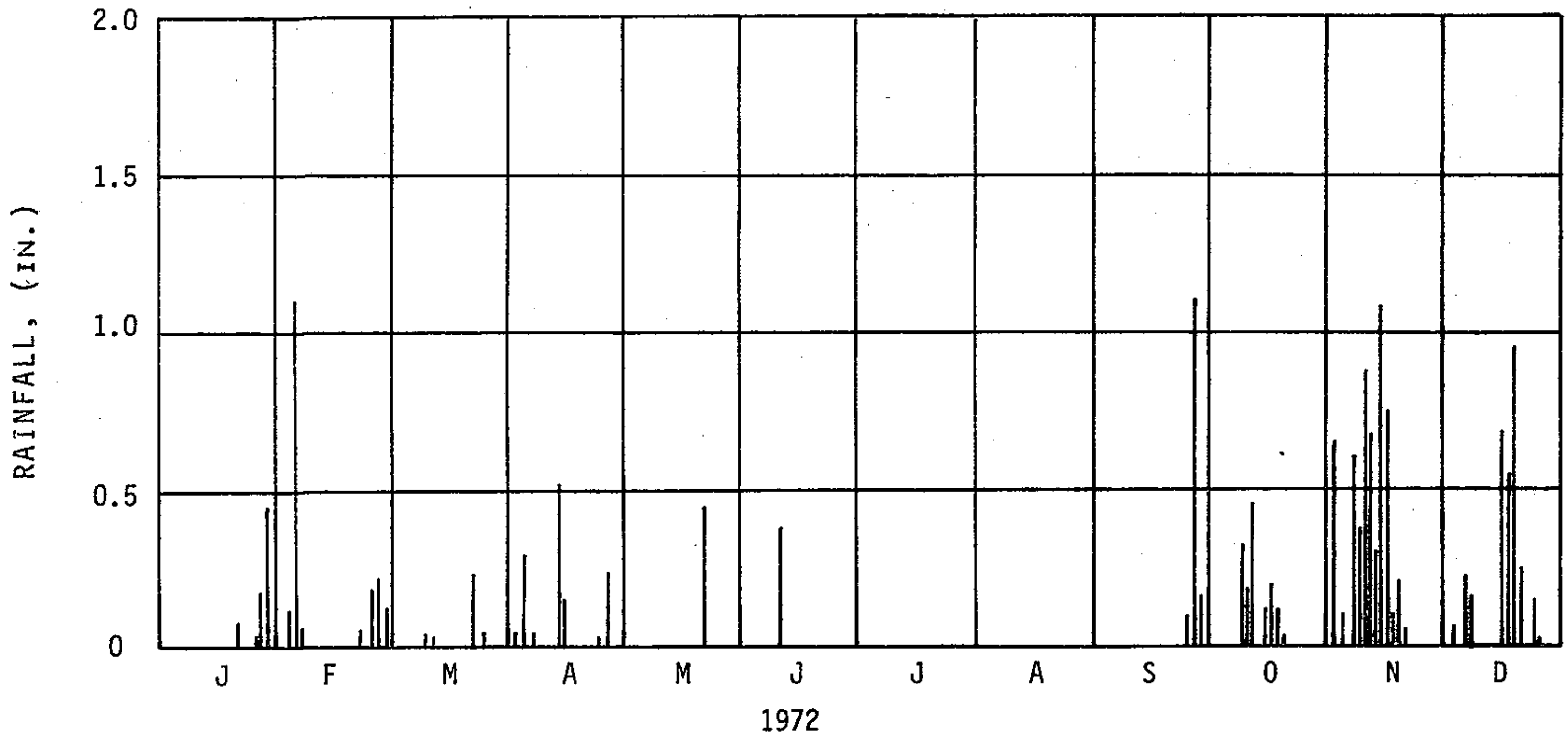


Fig. C-18. Rainfall events at Airfield A in 1972.

APPENDIX D

Field Investigations - Airfield E

CONTENTS

FIGURES

1 GENERAL INFORMATION

Pavements at this air base have been constructed at various times since before 1944, with the primary pavements that carry the heavier planes being built largely in the late 1950's. The field is in a fairly heavy precipitation area (30 inches or more of rain annually plus several feet of snow - see Fig. D-14) and relatively severe winters (1100 Degree days/year). Although it has had rather heavy traffic, the pavements generally appear to have withstood the traffic with comparatively minor serious damage. The air base is constructed on glacial lake deposits with sandy soils overlying varved silts and clays. It was first inspected by the writer (with a W.E.S. pavement condition survey team) on August 21-23, 1972.

One of the primary reasons for selecting this air base as a field investigation site was the belief that its apparently good performance was due to appreciable beneficial drainage into the sandy subgrade. After installing a number of small-diameter pipe observation wells in several of the pavements (on November 9 and 10, 1972), in-place permeability tests that were made in the wells indicated that the compacted sand subgrade may have coefficients of permeability in the range of 1×10^{-6} cm/sec (0.002 ft/day) or less. This suggests that downward drainage may be much slower than was originally thought. Some of the holes were drilled into pavements consisting of 6-in. to 7-in. thick AC pavements over coarse broken stone, locally called "trap rock." Where this stone was used it evidently bleeds excess water away from the crown areas of pavements (where the heavy traffic is) and provides protection against excess water, and it is felt that this may be a factor of importance at this air base.

Coarse rock such as the "trap rock" used here has extremely high permeability (generally over 30 cm/sec), and if a base drainage layer of this kind of material has collector pipes and outlets for gravity drainage it provides the best kind of drainage system for air bases.

This air base has an active crack sealing and surface sealing program under way. Much use is made of slurry seals on pavements that become cracked, and joints are being cleaned, routed when necessary, and sealed on a continuing basis. The Base Civil Engineer's office considers that good surface drainage is important, and any depressions or ruts that developed in taxiways or other important pavements have had the grade restored. Most of Taxiway G has a central "keel" section that was removed and strengthened.

The surface drainage system includes a large number of grated inlets in areas adjacent to the pavements, and within large apron areas. Except for collection of grass over some of the inlets in non-paved areas, and minor amounts of surface erosion near some of these inlets, there appear to be no major maintenance problems with the surface drainage system.

In a few areas, particularly where surface drainage was hampered by very flat surface slopes, stains on some of the pavements at joints suggested that there may be some internal flooding of pavements and occasional bleeding.

2 INSTALLATION OF OBSERVATION WELLS

An improvised drilling rig was used for putting a number of small-diameter pipe observation wells into pavements at several locations on November 9 and 10, 1972. Because of the time needed to drill and install wells, none were put in the main runway, since it could not be closed to traffic for the amount of time that would have been required. Locations of the eight wells are shown on the plan in Fig. D-1. Figures D-2, D-3, and D-4 show the drilling equipment used. The appearances of wells during installation and after completion are shown in Figures D-5 through D-9.

A rotary drill using an NX diamond bit was used for starting all of the holes. All were in AC pavements with the exception of Well 6, which was cored through 20 inches of PCC in the SW Warm-up Apron and Taxiway near the SAC Alert Area. Driving methods were used to make additional holes below the cored depth.

The procedures used in installing the wells were as follows: (1) holes approximately 3 inches in diameter were cored through the pavement and into the base until no more progress could be made; (2) additional depth of hole was made when appropriate by driving sampling tools and bits into the material; (3) samples were extracted, when possible, for visual examination and classification of materials penetrated; (4) sufficient pea gravel was placed in the holes to fill the part below the 1-1/4 inch diameter pipe, and the top of the pipe was adjusted carefully so that with a plug screwed in, the installation would be 1/8 to 1/4 inch below the surface of the surrounding pavement; (5) with the pipe centered, additional pea gravel was placed in the annular space between the pipe and the walls of the hole to within 5 or 6 inches of the top, and compacted by pouring water into the pea gravel and tamping with a rod; (6) fast-setting sand-cement grout was then placed in the annular space around the top part of the pipe to seal the pipe and hold it firmly in place; and (7) a vented plug was screwed in under firm hand pressure, making sure that the top of the plug was slightly below the surface of the pavement, as already noted. Logs of the holes and sections through the wells are given in Figures D-10, D-11, and D-12.

3 IN-PLACE PERMEABILITY TESTS

After each well was completed, water level readings were made for comparison with equilibrium readings later on. In the afternoon of the second day of the work (1-1/2 days of drilling time were required to install the wells), the writer, with the help of a member of the Base Civil Engineer's office, made in-place permeability tests by pouring water into the wells and observing the rates of fall after the pouring was stopped. Three of the wells were bottomed in coarse, broken "trap rock" grading from 1-1/2 inches to 1/4 inch in size, which was too permeable to test more than very approximately. Using rates of fall of water in the other wells, and values for i and A that were estimated from well dimensions, etc., coefficients of permeability were calculated with Darcy's law. According to these calculations, which are somewhat approximate, the gravel base course under the pavements is estimated to have in-place coefficients of permeability of 0.01 cm/sec (30 ft/day) or less. The compacted sand subgrade has a coefficient of permeability in the order of 1×10^{-6} cm/sec (0.002 ft/day), or possibly somewhat less. In several cases, the tests represent combined flows into bases and subgrade; hence the coefficients for the individual layers can only be estimated. Field permeability test data are plotted on graphs in Fig. D-13.

4 SOUNDINGS IN OBSERVATION WELLS

Wells were installed at this air base even though it was rather late in the year, and it was unlikely that much rain would fall before freezing weather would set in. A year before, for example, there was no rain from early in November, 1971, to the early part of April, 1972. It was felt, however, that this field should be used for one of the field investigation sites because it seemed to have better-than-average subsurface drainage. Also, it was felt that useful information about the permeability and type of base and subgrade could be obtained, even though only limited information about the build-up of saturation might be available for the preparation of this report. This turned out to be the case. Although a few inches of rain fell soon after the installation, the weather soon turned cold and the pavements became covered with ice and snow, making it impossible to locate most of the wells.

On November 15 the wells were inspected by the Base Civil Engineer's office after a night of snow. No water was found in any of the holes. On November 20, following a day in which 0.91 inch of rain had fallen, water was found 6.5 inches below the pavement top in Well 2, and all of the other wells were dry (at 8:40 a. m.). At 11:45 a.m. the water level in Well 2 had lowered to 10.3 inches below the top of the pavement, and at 3:00 p.m. it was at 11.8 in. depth. On November 22, Well 2 was dry after a period of no precipitation. On November 26, water was at 10.5 inches depth in Well 2 at 1:15 p.m. and at 12.9 in. depth at 4:30 p.m. All of the other wells were dry. On November 27, there was no water in any of the wells, although there had been 1.0 inch of precipitation the previous day. All of these readings were supplied by the Base Civil Engineer's office.

5 DISCUSSION OF THE PAVEMENTS TESTED

Taxiway G at Calibration Hardstand. At this location, some staining near joints and cracks suggested that there might be some bleeding or surging under wheel impacts or gravity drainage out of saturated pavements. Wells 1 to 3 were located here (see Fig. D-10). The drilling indicated that there is from 7 to 12 inches of AC over a sandy gravel base which is on a dense sandy subgrade of relatively low permeability. As noted under Section 4, free water had been observed in Well 2 during several of the times readings were made after the wells were installed and before the freezing weather had set in. The falling head permeability tests that were made here indicated coefficients of permeability in the order of 3×10^{-4} cm/sec (1 ft/day) for the sandy gravel base, and in the order of 1×10^{-6} cm/sec (0.002 ft/day) for the sandy subgrade (see Fig. D-13).

Taxiway G at Dock 32. At this place, Well 4 was drilled through 6 inches of AC and a few inches into the crushed "trap rock" base (see Fig. D-11). Although the AC pavement at this location appeared structurally sound, with no evident cracking or other distress, other areas along this taxiway have appreciable amounts of wide cracks, which are being covered with slurry seals.

Taxiway G at Dock 10. At this location, Well 5 was drilled through 6 inches of AC, and about 6 inches of sandy gravel base, into dense, layered sandy subgrade material (see Fig. D-11). The field permeability testing indicated the gravelly base had a coefficient of permeability in the order of 6×10^{-4} cm/sec (2 ft/day), but the sandy subgrade is very impermeable (see Fig. D-13). The AC pavement in the vicinity of Well 5 is rather badly cracked (see Fig. D-7). The drainability indicated by the tests at Well 5 is rather low (Fig. D-13), and this may be a factor in the apparent distress of the pavement at this location.

SW Warm-up Apron and Taxiway Near SAC Alert Area. At this location, three wells were cored into the pavements: Well 6, in the 20-inch thick PCC pavement on CTB over dense, sandy subgrade; and Wells 7 and 8, in the 7-inch thick AC pavement over coarse trap rock (see Fig. D-12). Some staining at pavement joints in this area suggested the possibility of bleeding of the PCC pavement during periods of heavy precipitation. According to the tests that were made here (see Fig. D-13), the coefficient of permeability of the sandy subgrade appears to be relatively low; hence it seems possible that during periods of heavy rainfall there may be some internal flooding of the PCC pavement structural section. The trap rock provides fast drainage under the high portions of the AC pavement to lower elevations; and the pavement at higher elevation is in excellent condition. As already noted, coarse rock of the kind used here, if provided with collector pipes and outlet pipes giving gravity drainage, can provide essentially 100% drainage for pavements of any widths. As pointed out in the basic report, bottom drainage out of upper pavement and base layers is the most effective kind.

6 DISCUSSION OF DRAINAGE CONDITIONS

Airfield E is located in a region where very heavy rains fall during summer months, rather light and intermittent rains occur during the autumn and fall months, and substantial amounts of cold weather and snow prevail during the winter months. Figure D-14 is a plot of the rainfall events near the air base in 1972. It can be seen that over 4 inches of rain fell in April, more than 6 inches in May, over 8 inches in June, and nearly 4 inches in July. There is very heavy precipitation available to saturate pavements for a period of approximetely 4 months, with much less during the balance of the year.

Although the natural subgrade at Westover AFB is sandy soil, the drilling and testing for this project indicates that when the sand is thoroughly compacted, as in the construction of the major pavements at this base, its coefficient of permeability may be in the order of 1×10^{-6} cm/sec (0.002 ft/day), or less, and downward beneficial drainage may be quite slow.

In some of the pavement areas where holes were drilled for the installation of observation wells, the AC pavements had been constructed on very coarse "trap rock," which has very high permeability. It appears that where this coarse rock was used, free water which enters the pavements is able to drain rapidly out from under the crown areas, where the traffic is generally concentrated, thus providing substantial benefits to the pavements in these areas.

An examination of the weather records for this area suggests that rainfalls in excess of 0.1 inch may occur more than 50 times in a year, and those in excess of 0.2 inch can be expected about 40 times a year. Since the observation wells were put in late in the year (which was necessary to be able to use this base as one of the field investigation sites), it has not been possible to fully evaluate the effectiveness of subdrainage at this base in time for this report. It is hoped, however, that the Base Civil Engineer's office will be able to observe saturation in the pavements during the next heavy rainfall season, as this information should be of value to his office in assessing the year-round, annual drainage condition of the pavements at the locations where the wells were installed.

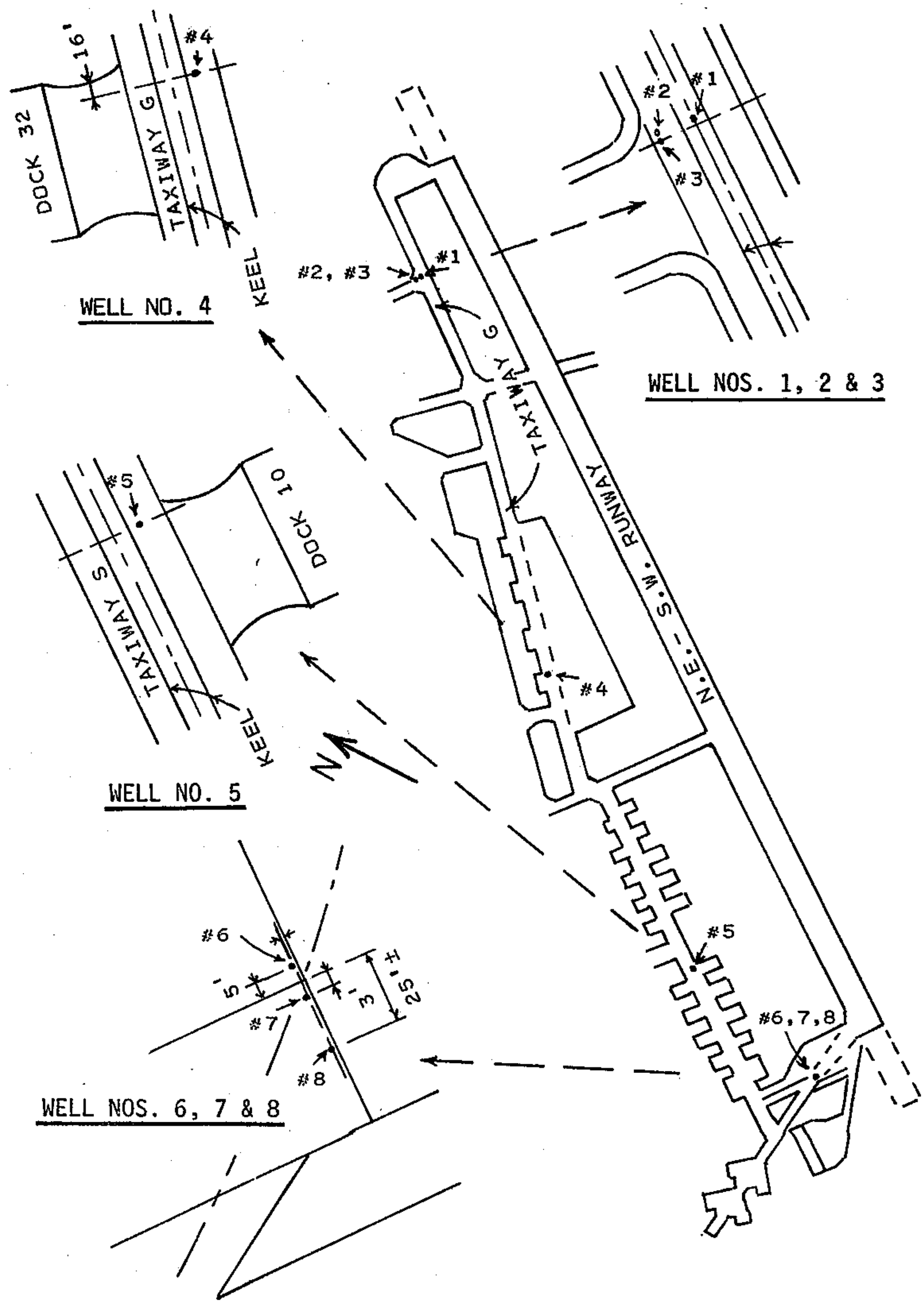


Figure D-1. Locations of observation wells in pavements, Airfield E.

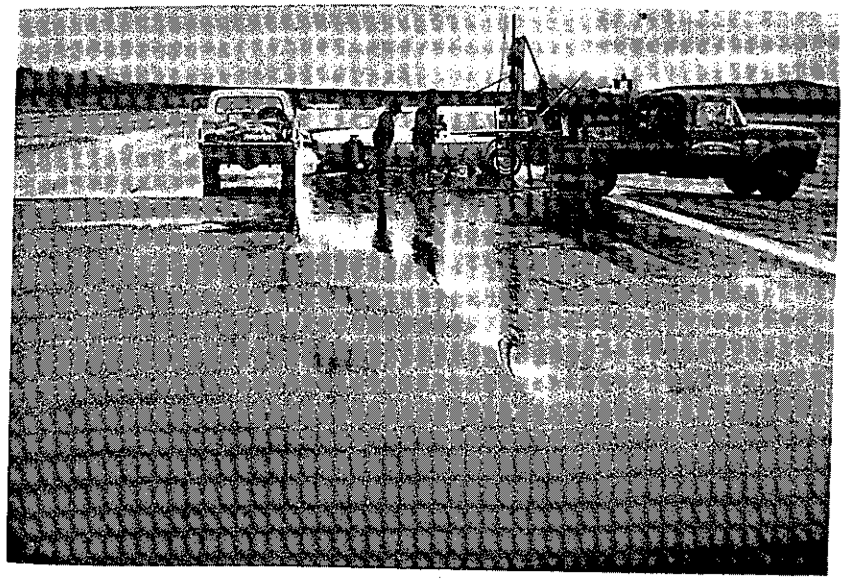


Figure D-2. Photo of drilling equipment at Well 1; near centerline of Taxiway G at Calibration Hardstand; stopped raining about 2 hours ago; some water entrapment on surface of pavement.

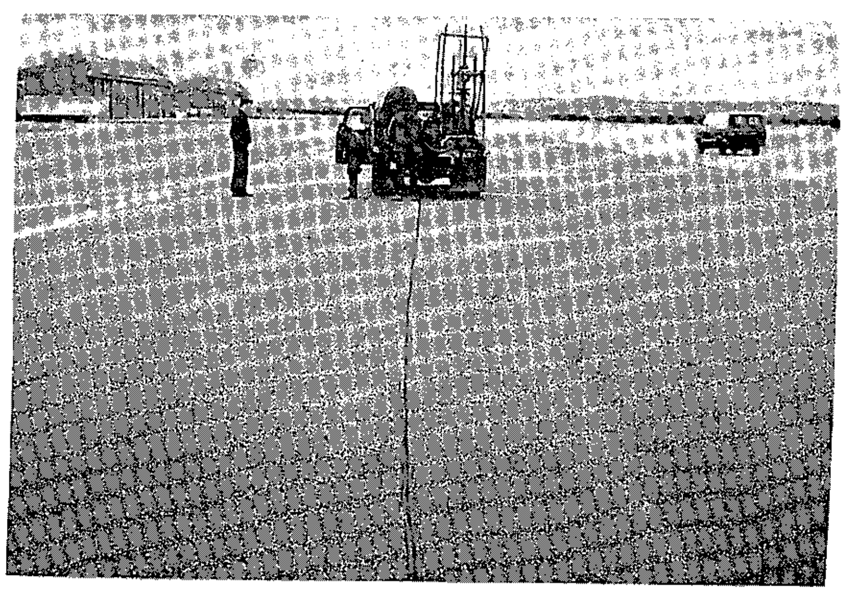


Figure D-3. Photo of drilling equipment at Well 4; Taxiway G at Dock 32; base course under 6-in. thick AC pavement is very open-graded trap rock.

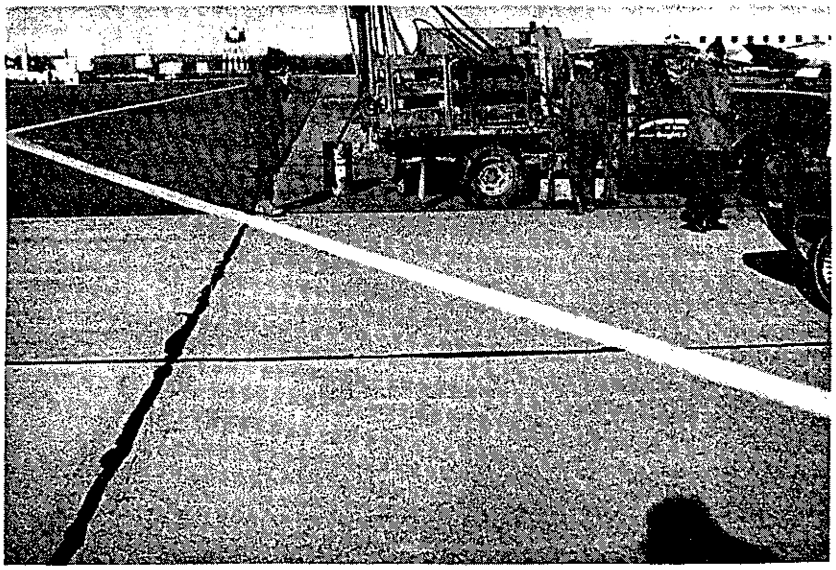


Figure D-4. View of drilling equipment at Well 6; is in 20-in. thick PCC at SW Warm-up Apron and Taxiway; dark stains suggest some bleeding may occur here; no excess water at time of drilling.

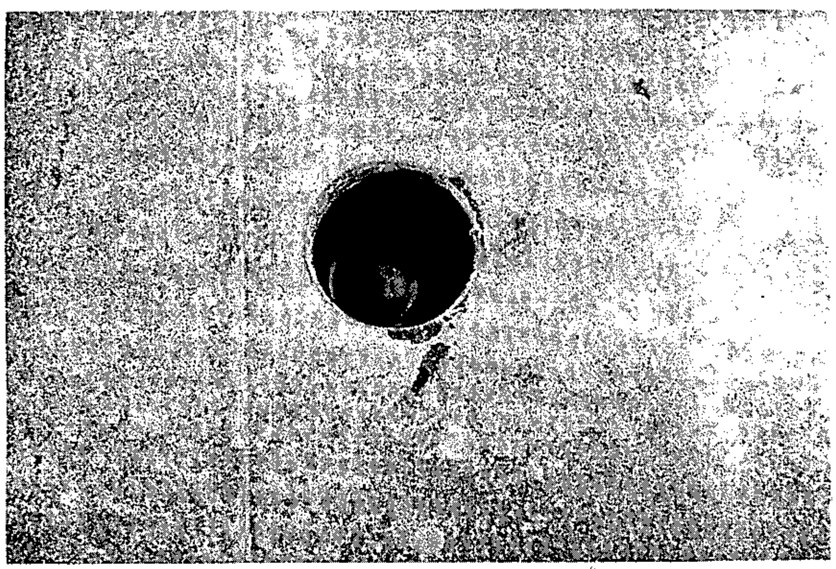


Figure D-5. Looking down into hole 2 after drilling to 18-in. depth; water stood 12 inches below top of pavement--from water used in drilling hole; light is being reflected off water in hole.

APPENDIX E

Field Investigations - Airfield F

CONTENTS

Figure D-8. Photo at Wells 6-8, looking SW; the stains are from drilling; Well 6 in foreground is in 20-in. PCC; Wells 7 and 8 are in 7-in. AC on coarse trap rock.

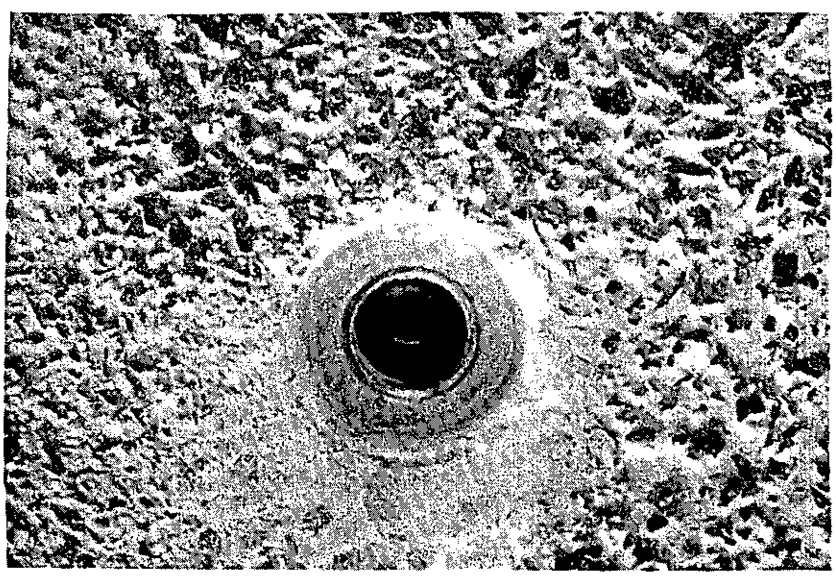
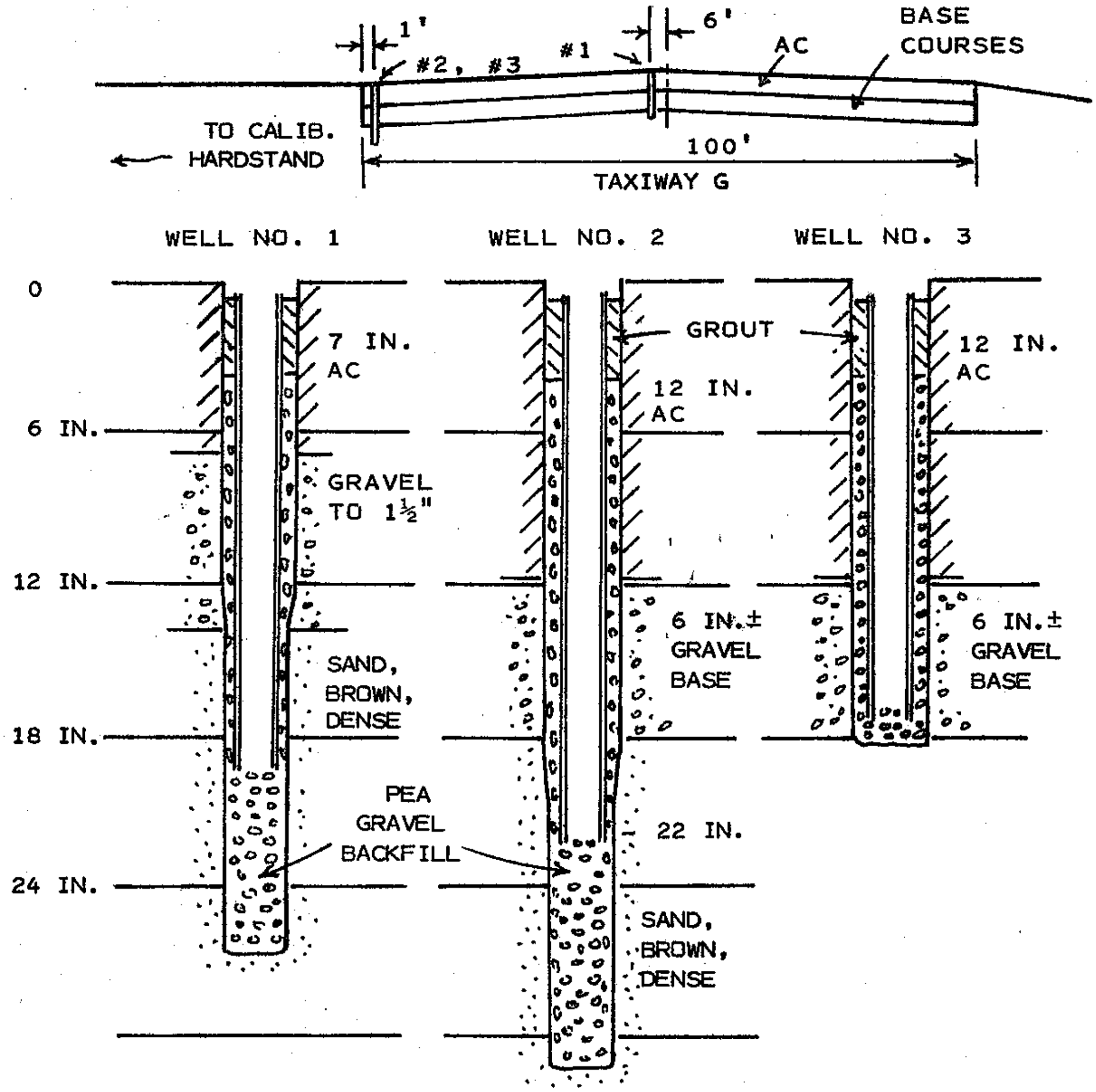


Figure D-9. Looking down into Well 6, falling head permeability test in progress; water in well has fallen to 4.5 inches below top of pavement after 6 minutes; average k is about 7×10^{-5} cm/sec (0.2 ft/day).

TAXIWAY G AT CALIBRATION HARDSTAND



NOTES: HOLES APPROXIMATELY 3 IN. DIAMETER; PEA GRAVEL USED FOR BACKFILL; FAST-SETTING SAND-CEMENT GROUT USED FOR SEALING UPPER PARTS OF HOLES AROUND 1¼ IN. GALV. PIPE. VENTED PLUGS IN EXCEPT WHEN TAKING READINGS.

Figure D-10. Logs of wells 1 to 3.

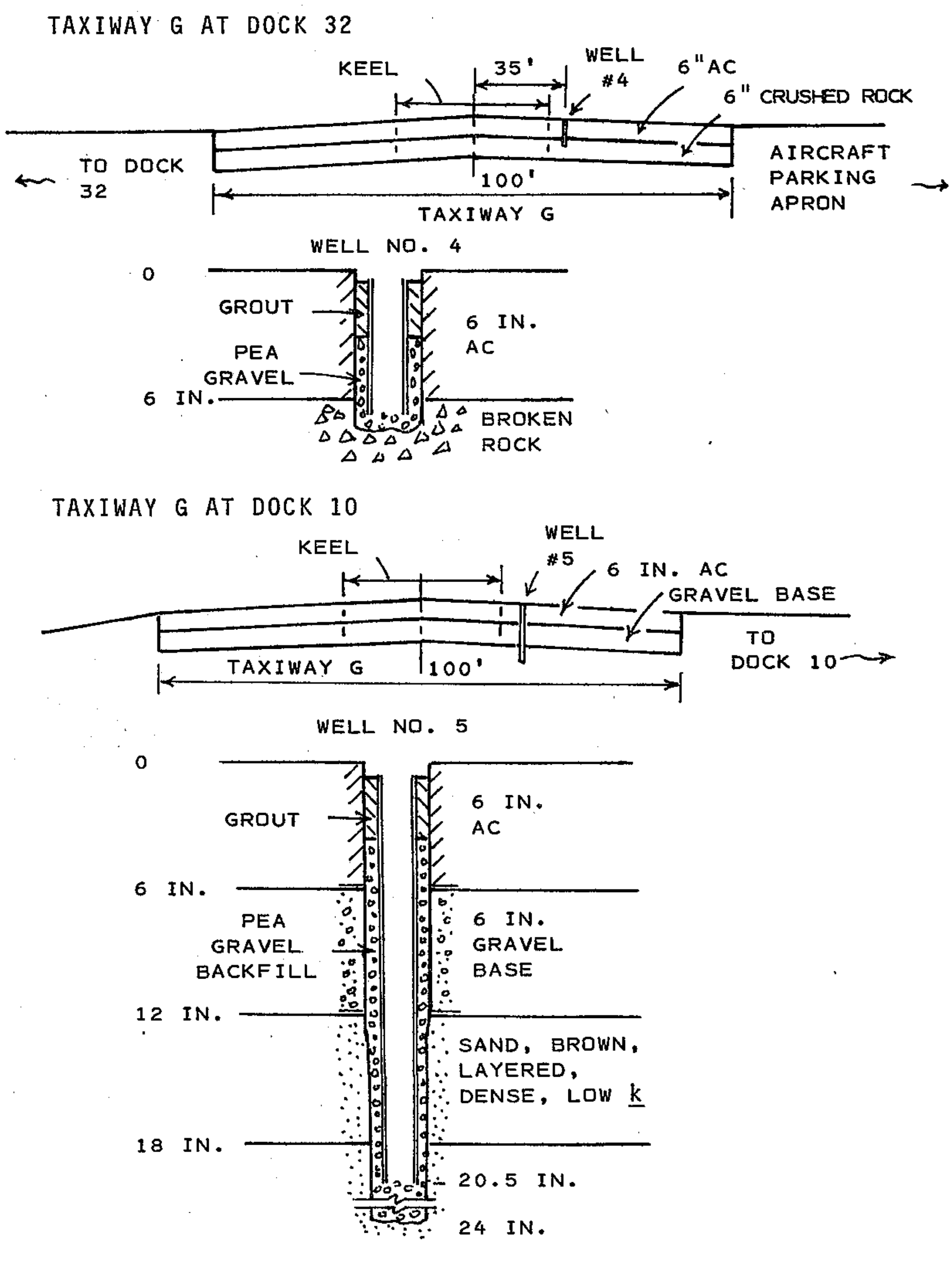


Figure D-11. Logs of wells 4 and 5.

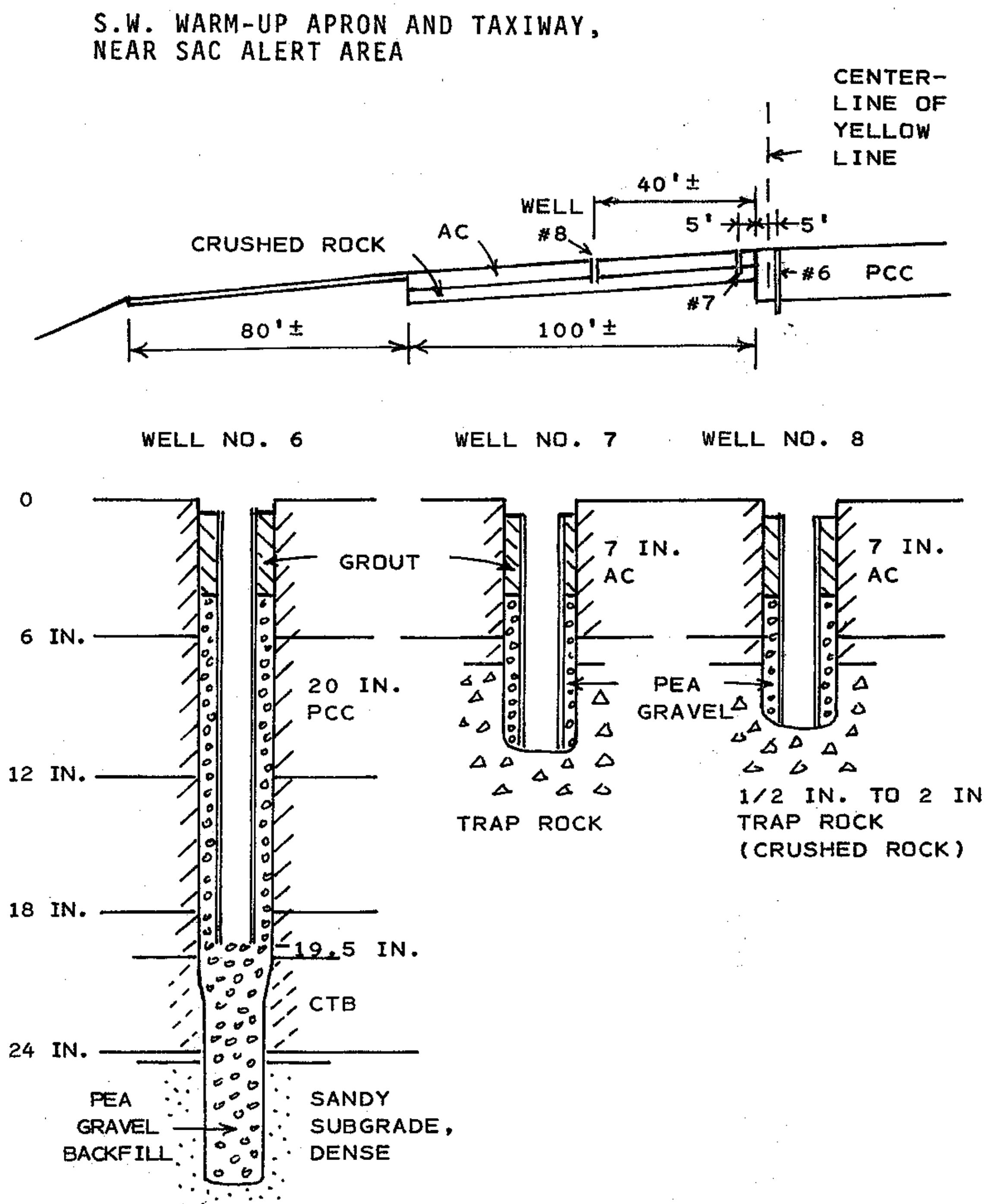
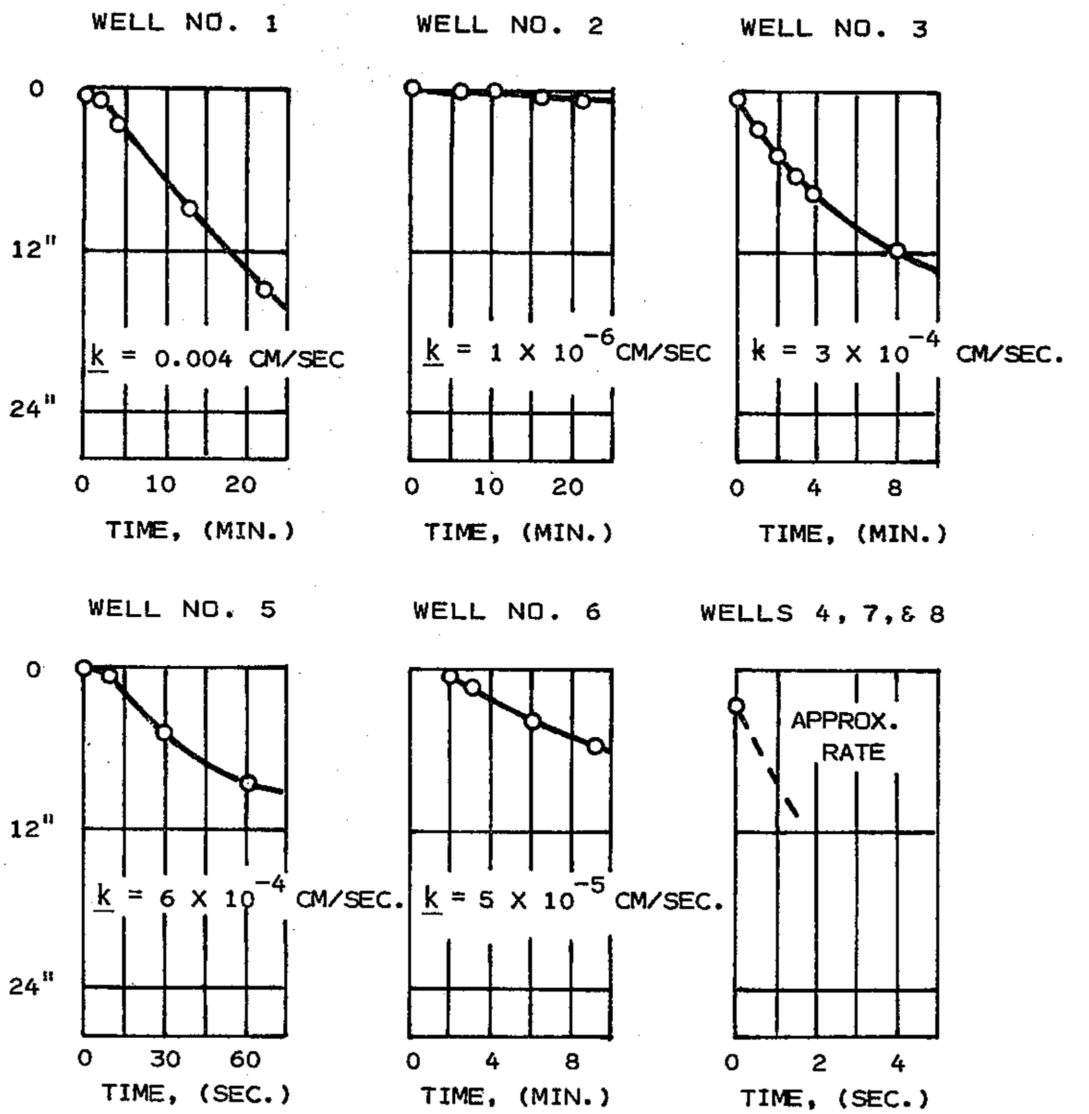
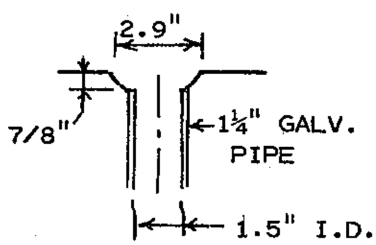


Figure D-12. Logs of wells 6 to 8.





WELL TOP DETAIL

NOTES: OBSERVATION WELLS INSTALLED NOV. 9 AND 10, 1972.
WELLS 4, 7, AND 8 BOTTOMED ON COARSE TRAP ROCK; HOLES COULD NOT BE FILLED BY POURING FROM PAIL; EXTREMELY PERMEABLE MATERIAL.

Figure D-13. In-place permeability test data.

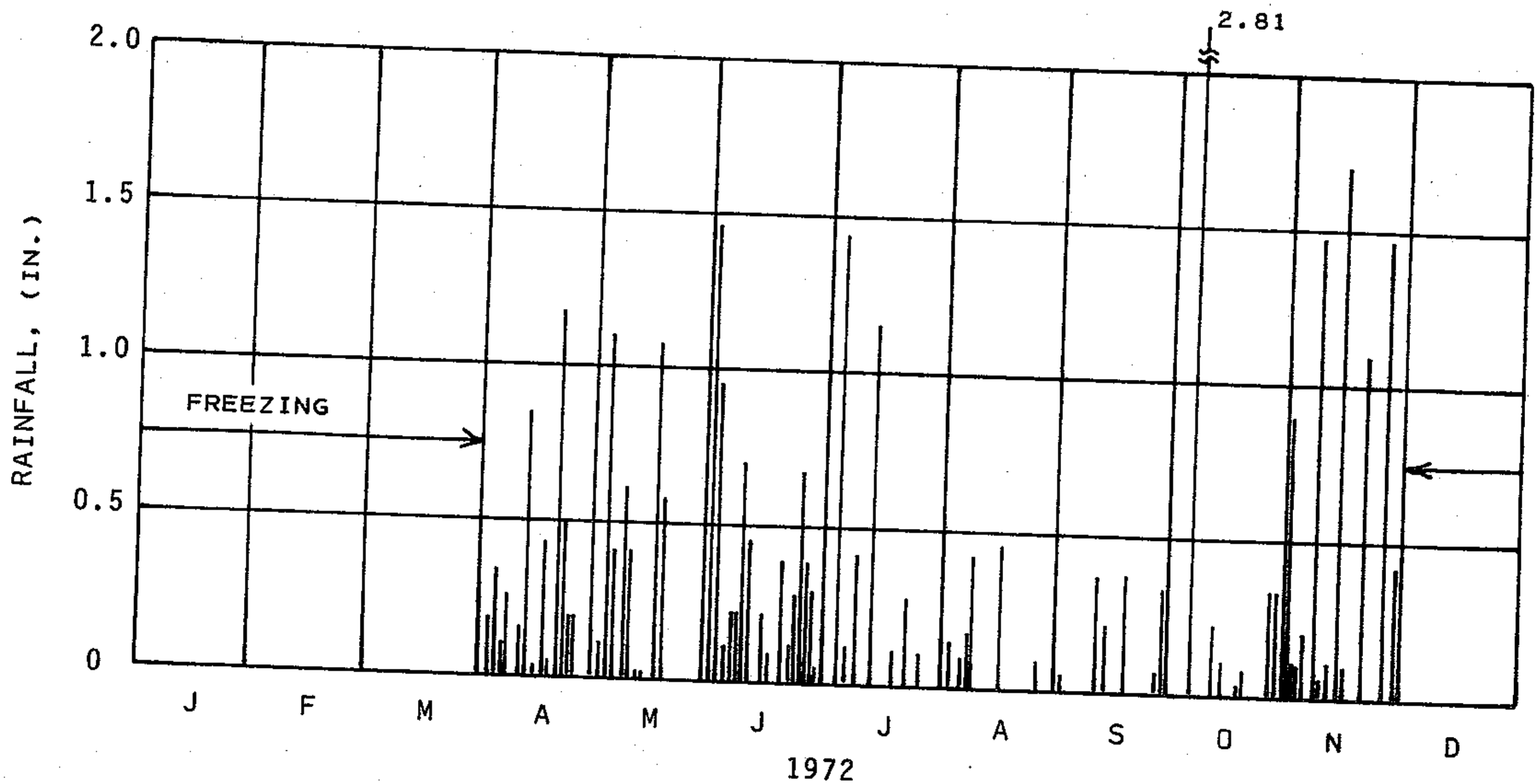


Figure D-14. Rainfall events near Airfield E in 1972.

APPENDIX E

Field Investigations - Airfield F

CONTENTS

FIGURES

1 GENERAL INFORMATION

This air base is located in an area of rather heavy rainfall (40 inches/year), with considerable cold weather in the winter. The terrain slopes to the southwest, and the southeast end of the field occasionally has several feet of water over the pavements when water backs up behind a flood control dam about a mile downstream from the base. Various parts of the pavement system have been constructed at various times since 1947; however, the primary pavements, the heavy bomber apron, runway, and taxiways were constructed in 1959-60. The arrangement of the pavements is shown by an aerial in Fig. E-1.

The natural subgrade soils at the air base vary from clays, silts, clay gravels and silty gravels. During construction, frost susceptible materials were removed to a depth of several feet under all of the pavements and replaced with non-frost susceptible "bank run" material obtained from local borrow pits. A bag of "typical" material was obtained from a borrow pit bank at the lower end of the reservation on August 31, 1972 and tested in a laboratory, with the following results:

Size or Sieve No.	Percent Passing
1-1/2 in.	100
1/2 in.	75
No. 4	42
No. 8	28
No. 16	22
No. 30	14
No. 50	9
No. 100	7
No. 200	5.5

This material had a Sand Equivalent of 40. Even though the native clay soils were removed down to natural gravels under the SAC pavements and replaced with this kind of non-frost susceptible material, the compacted pit run gravels have relatively low permeabilities, and drainage into the subgrade of these pavements is quite slow.

Downward beneficial drainage of most of the pavements at Airfield E appears to be almost negligible. During a site inspection that was made by the writer in company with a WES pavement condition survey team on August 31 and September 1, 1972, engineers at the Base Civil Engineer's office said that they often see water seeping out of the joints of the primary PCC pavements after heavy rains. For the most part, these pavements are in "bathtubs" and water stays in the structural sections for prolonged periods during and after rainstorms. When the Base Civil Engineer's office had holes cored through the pavements of the main runway and other pavements, water often rose to the top of the cored holes, indicating the structural sections contain free water under sufficient head to rise to the surface.

"D" cracking and blow-ups are common problems at this base. It appears that these problems may to a large degree be caused by excess water in the structural sections. Blow-ups occur during warm to hot weather and are believed to be caused by heavy expansion pressures due to the heat, and excess water which stays in the sections because of slow drainage. Repairs to the main runway have included extensive epoxy repairing in 1964, and a 4-inch overlay in 1971. It seems likely that many of these repairs might have been averted, or at least been extended over a much longer period of time if these pavements had been constructed as rapidly draining systems.

"D" cracking and blow-ups are a serious nuisance, and create a safety hazard to jet aircraft, as the loosened material on the pavement can be sucked into the jets, destroying them or causing expensive repairs. This danger of foreign object damage (FOD) is a major problem to the Air Force, and throughout the world costs millions of dollars each year. Also, the roughness caused by developing blow-ups creates problems in the operation of aircraft.

The shoulders of the main pavements as well as other less important pavements are showing extensive cracking and general deterioration, which is believed to be caused by frost action in these pavements, and which is aggravated by the prolonged retention of water in and under these relatively thin, undrained pavements. Grass and weeds are growing in cracks and joints in many shoulder pavements, which is evidence that an abundant supply of water must be available to sustain this growth. This type of condition can, however, be seen in virtually every military and non-military airfield in rainy regions of the country.

Surface drainage at this airfield appears to be adequate, and there has been little or no silting of drainage pipes.

After completion of the data collection and site inspection parts of this project, Airfield F was selected for one of the sites for field investigations. Primary reasons for selecting this base are the following:

1 It has had large numbers of heavy load repetitions.

2 It is in a high rainfall area.

3 There was evidence of poor subgrade drainage.

4 Extensive pavement maintenance has been required over the years.

2 INSTALLATION OF OBSERVATION WELLS

On October 18, 1972, ten small-diameter pipe observation wells were installed at selected locations. Because of aircraft traffic schedules, it was not possible to close down the runway for the amount of time that would have been needed to drill holes and install wells; hence locations were selected at two places on the taxiways serving the operations of interest, and two additional wells were drilled in the NE Warm-up Apron. The locations of the wells are shown on the plan in Fig. 1. Cross sections through the pavements at the test locations, and logs of the holes and sections through the wells are given in Figures E-2, E-3, and E-4. These locations were selected in consultation with and with the approval of the Base Civil Engineer's office, as the best of available locations.

Under subcontract with the writer, a testing laboratory furnished a Mobile Drill with drilling tools and accessories to do the necessary drilling and install the observation wells. They used an NX diamond bit to core PCC pavements, chopping bits to drill into AC pavements and bases, and a split-spoon drive sampler to obtain samples for inspection and classification. The following procedures were used for installing the wells: (1) holes approximately 3 inches in diameter were made through the pavements and into the bases and in some cases into the non-frost susceptible subgrade backfill; (2) sufficient pea gravel was placed in the bottom of the holes to allow the pipes to be set to the desired level; (3) the pipes were set on the pea gravel backfill, carefully adjusted to the right vertical elevation by either adding small amounts of pea gravel or by pounding the pipes slightly, so that the finished installation with plugs in place would be 1/8 inch to 1/4 inch below the surface of the adjacent pavement; (4) additional pea gravel was placed in the annular space around the pipes to within 5 or 6 inches of the top of the hole, and compacted with water and a small rod; (5) fast-setting sand-cement grout was then placed in the upper part of the annular ring to seal the upper end of the pipe and secure it rigidly to the pavement; (6) a vented plug was screwed in place to firm hand pressure, making sure that the top of the plug was slightly below the top of the pavement.

3 IN-PLACE PERMEABILITY TESTS

After each well was completed, water level readings were made for comparison with equilibrium readings later on. A day after the installation (October 19, 1972), the writer, with the help of a member of the Base Civil Engineer's office, made in-place permeability tests in each of the holes by pouring water into the wells and observing the rate of fall of the water level. These readings are plotted on small graphs in Figures E-5 to E-9. From the rates of fall, coefficients of permeability were calculated using Darcy's law, with values of i and A estimated from the dimensions of the hole, and estimated penetration of water into the surrounding materials. The calculated values, which are shown in the right-hand graphs in Figures E-5 to E-9, represent <u>average</u> values for the depths of formations tested, and they are somewhat approximate.

Permeability values for aggregate bases under PCC pavements range from 3×10^{-6} cm/sec to 0.01 cm/sec (0.01 ft/day to 30 ft/day); those for AC shoulder areas vary from 1×10^{-6} to 3×10^{-5} cm/sec (0.003 to 0.1 ft/day).

On the basis of the observations during the drilling, and the in-place permeabilities calculated from these tests, it appears that major differences in the permeability of the bases occur within small horizontal distances. There appear to be pockets of rather permeable material, probably surrounded by materials of much lower permeability.

4 SOUNDINGS IN OBSERVATION WELLS

The permeability testing described above was performed to try to evaluate the general levels of permeabilities of the formations in which wells were installed. This information is useful in studying rates of drainage into and out of the structural sections. The other purpose of these wells was to monitor groundwater mounds and get whatever other useful information might be obtained.

Under the contract agreement with testing laboratory, soundings were made a number of times after the installation (see Figures E-5 to E-9). The intent of these readings was to try to determine how high the saturation builds up within the structural sections during and following substantial rainfalls, and the rate of fall after it stops raining. On the days of the installation, it was seen, for example, that an artesian flow was coming out of lower portions of the NE Warm-up Apron (where Wells 9 and 10 were installed) after a light rainfall of about 0.02 inches in 4 or 5 hours. The readings that have been made since that time show that many of the wells became filled to overflowing after rainfalls of moderate amounts in a few hours. Some of the wells have drained out completely within a day or so of dry weather, and others have had appreciable depths of water every time they have been read. It appears that the bottom surface of the PCC pavements in the SAC facilities are wet a great deal of the time (see water level profiles in Fig. E-10.

Since the taxiways are much narrower than the Main Runway, the rate of lowering of saturation within the taxiways is probably much more rapid than within the Main Runway; hence the runway pavement is no doubt being kept wet much longer than the taxiways. It is felt that possible differences in amounts of exposure to water may be a factor responsible for the large amount of "D" cracking that has occurred in the runway, while only minor amounts are beginning to show up in the taxiways within the past 2 or 3 years. This conclusion is offered, recognizing that it needs further verification.

Another major "find" of the soundings in the wells, was the discovery that within a month after installation the pea gravel backfill worked its way up to within 2 inches of the top of Well 5, which is located at a point that received an average of ten to twelve B-52's and KC-135's per day (see Fig. E-7). Professor Barenberg and other researchers have noted that heavy wheel load impacts on pavements filled with free water may produce actions comparable to "liquefaction" or to "quick-sand," in granular bases*. The powerful surges in water pressure created by the passing planes may be responsible for the movement of the pea gravel backfill under Well 5 upward into the pipe. As long as the base material is confined, it cannot move out from under the pavements, but in any place where its confinement is released (as at this well), it evidently tends to move. Probably, pulsating actions within bases at other airfields may be occurring under slabs where "geysers" have been seen under passing planes. This has been reported at many air bases, although evidently it has not been observed at this air base.

5 DISCUSSION OF THE PAVEMENTS TESTED

Taxiway 14. At this location, Wells 1 and 2 were cored into the PCC pavement and 3 and 4 were drilled into the AC shoulder (see Fig. E-3). The PCC pavement shows no physical distress, although the shoulders in this area are badly cracked. As may be seen in Figures E-5 and E-6, the water level builds up to the top of the pavement during showers, but drops rapidly to a foot or so below the surface after it stops raining. Lower parts of the structural section remain filled with free water a long time after each rain. As may be seen in Fig. E-10, the section is essentially in a "bathtub" for appreciable amounts of time.

Soundings of the depths to the bottoms of the wells have shown no tendency for the pea gravel backfill to work up in the pipes, as has been observed at other locations on this air base. The general appearance of pavements in this area is shown in Fig. E-11. A large amount of repair work is being required on the AC shoulders.

Taxiway 17, Adjacent to SAC Apron. At this location on the primary taxiway, Wells 5 and 6 were put in the PCC and 7 and 8 were installed in the AC shoulder, all on the southerly side of centerline (see Fig. E-3). The overall fluctuation pattern of water levels is generally similar to that of the wells in Taxiway 14, as just described, with the levels rising rapidly to the pavement surface during rains, and starting to fall rather rapidly after rains, but remaining in the pore spaces in lower parts of the structural section for the entire period of the readings (see Figures E-7 and E-8)

As noted before, the soundings of the depths to the bottoms of the wells revealed a major rising of the pea gravel backfill in Well 5 within a month after its installation, presumably due to pulsating pore pressures caused by heavy wheel loads. There was no sign of pavement distress at this location, so any pore pressure actions that are taking place evidently have not led to any apparent physical damage to the pavement. It is expected, however, that these kinds of actions ultimately shorten pavement life.

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* (Private communication between Dr. E. J. Barenberg and the author).

NE Warm-up Apron and Taxiway. This area was selected because of noticeable light stains showing apparent bleeding near the lower edge (see Fig. E-12). It was desired to verify the state of saturation under a pavement showing unmistakeable evidence of bleeding. The pavement had been given a tar rubber overlay (Figures E-2 and E-3), so there was no way of seeing the condition of joints in the 24-inch thick PCC pavement, although distinct reflection cracks were evident in the overlay. Well 9 was drilled at the crown, and Well 10 was put in about 17 feet from the lower outside edge (see Fig. E-4). The base course directly under the PCC pavement is relatively permeable, but there is no evident exit except by seepage downward or outward. As may be seen in Figure E-9, the water level is close to the surface at both locations during showers, and falls rapidly in Well 9 after it stops raining, but stays relatively high in Well 10 a long time after it stops raining. When Well 10 was first cored through the PCC pavement, a small artesian head caused water to flow out of the hole, even though only about 0.02 inch of rain was recorded that day before the hole was put in.

Observations in Wells 9 and 10 suggest that the bottoms of the PCC slabs in this area may be in water substantial amounts of time because of slow drainage of water out of the base course (Fig. E-10). Soundings of bottom depths of the wells indicate a possibility of pea gravel backfill working up a slight amount in Well 9 (Fig. E-9).

6 DISCUSSION OF DRAINAGE CONDITIONS

The natural subgrade materials at Airfield F are relatively impermeable, and downward beneficial drainage is very slow. Readings in the observation wells installed as part of this study indicate that water remains within the pore spaces of structural sections for long periods after rains, and the bottoms of many of the PCC pavements are in water for many months each year.

This airfield is located in a rather heavy rainfall area. A plot of rainfall events for a 12-month period near the base (Fig. E-14) shows that 40 to 50 significant rainfalls can be expected each year, distributed throughout most of the year. On the basis of the rainfall characteristics of the area, together with the low permeability of the subgrade materials lying under the pavements, it is estimated that some of the pavements may be submerged in free water for possibly 260 days each year, and that others (such as Well 9) may contain free water lesser amounts of time each year.

Although there has been no apparent structural damage to the heavy-duty pavements, the Main Runway has experienced major amounts of "D" cracking and joint problems. It is felt that the magnitude of these problems can be at least partly attributed to the slow drainability of these pavements, and their long exposure to free water. Thus, slow drainage is believed a major factor responsible for the high maintenance costs on the primary runway and other pavements at this air base.

Since so much of the life-cycle of pavements depends on the behavior of saturation mounds in structural sections, it is felt that the information obtained from the monitoring wells put in pavements at this base is a very valuable contribution to this study.

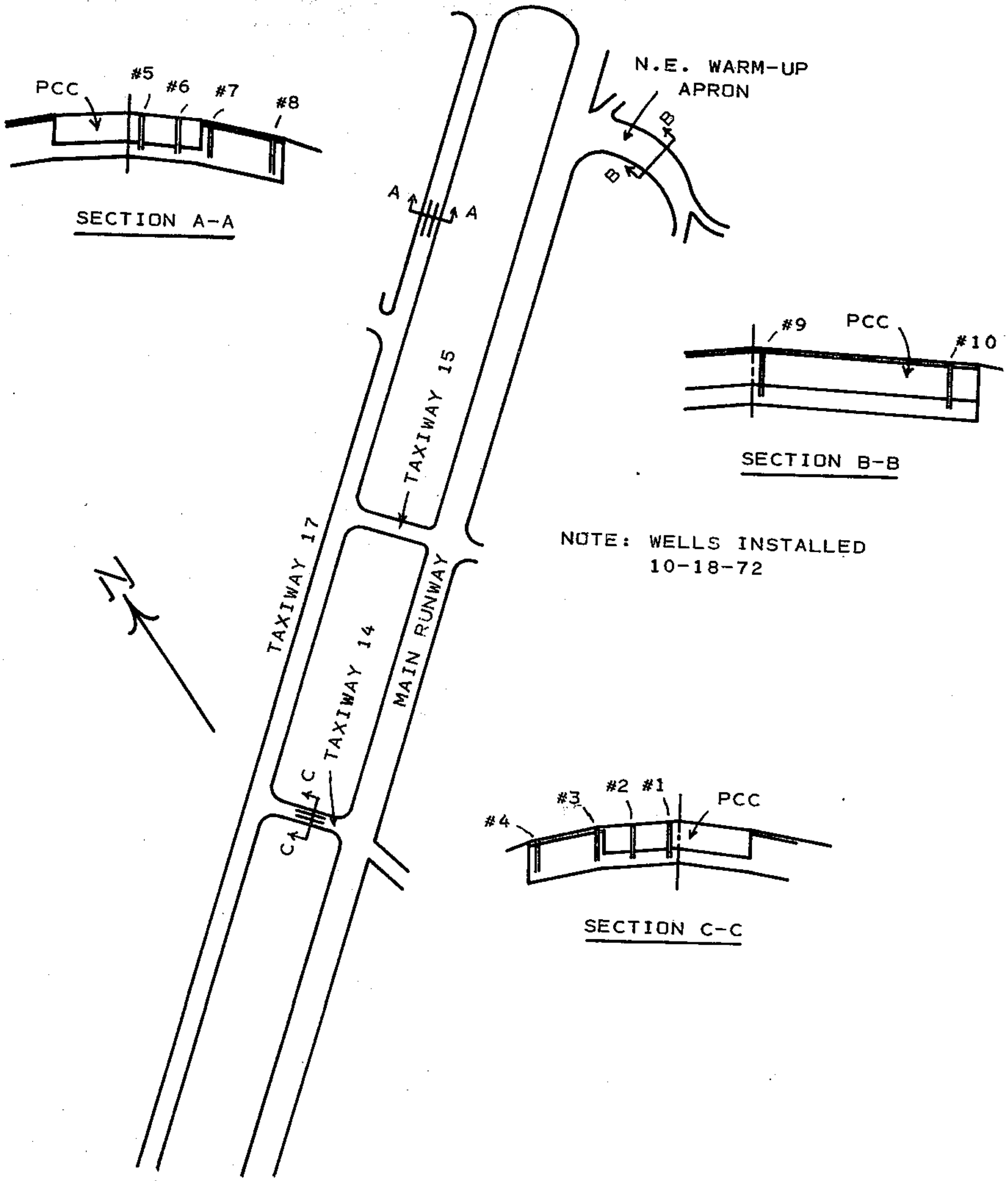

Figure E-1. Locations of observation wells in pavements, Airfield F.

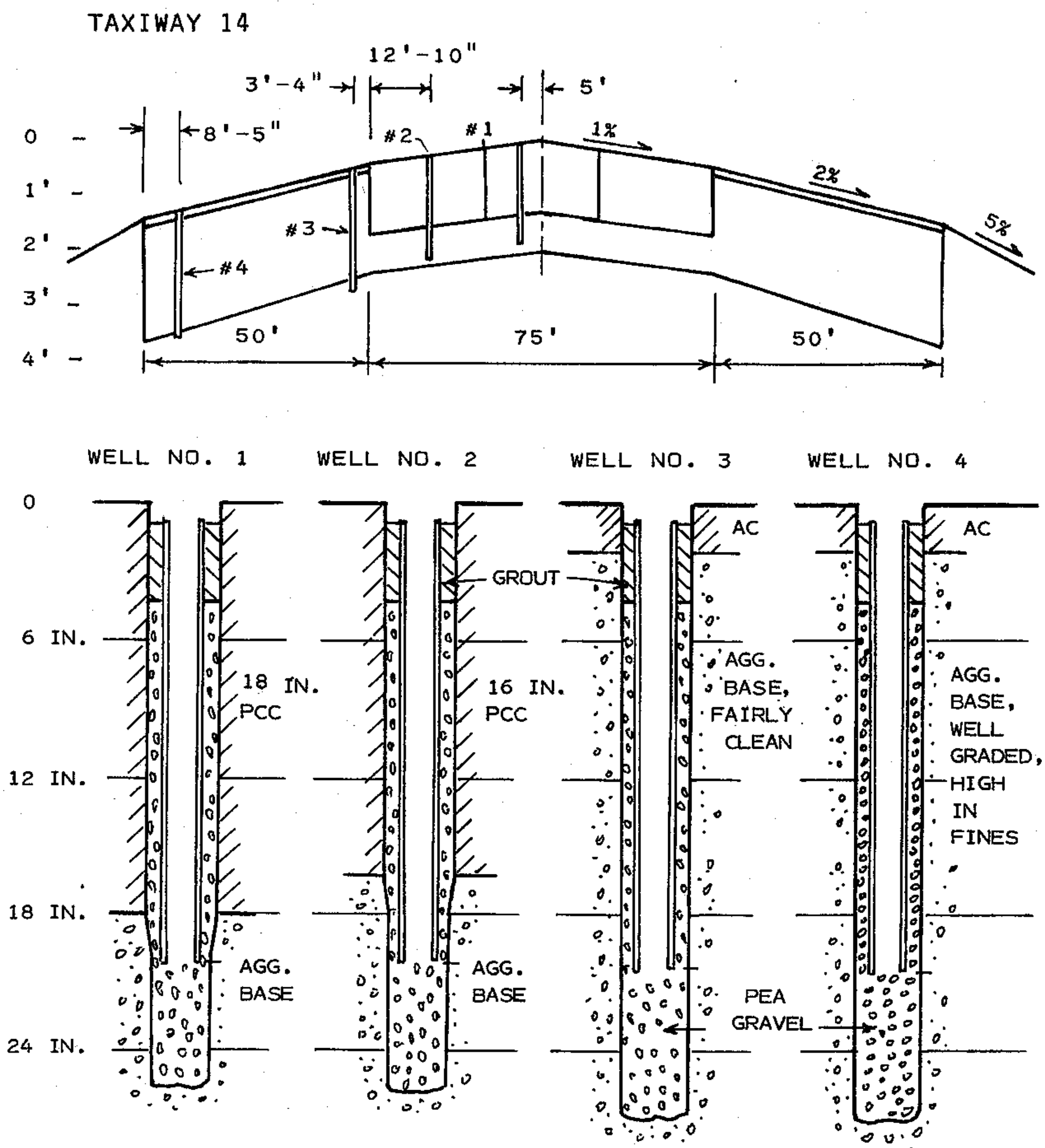

Figure E-2. Logs of wells 1 to 4.

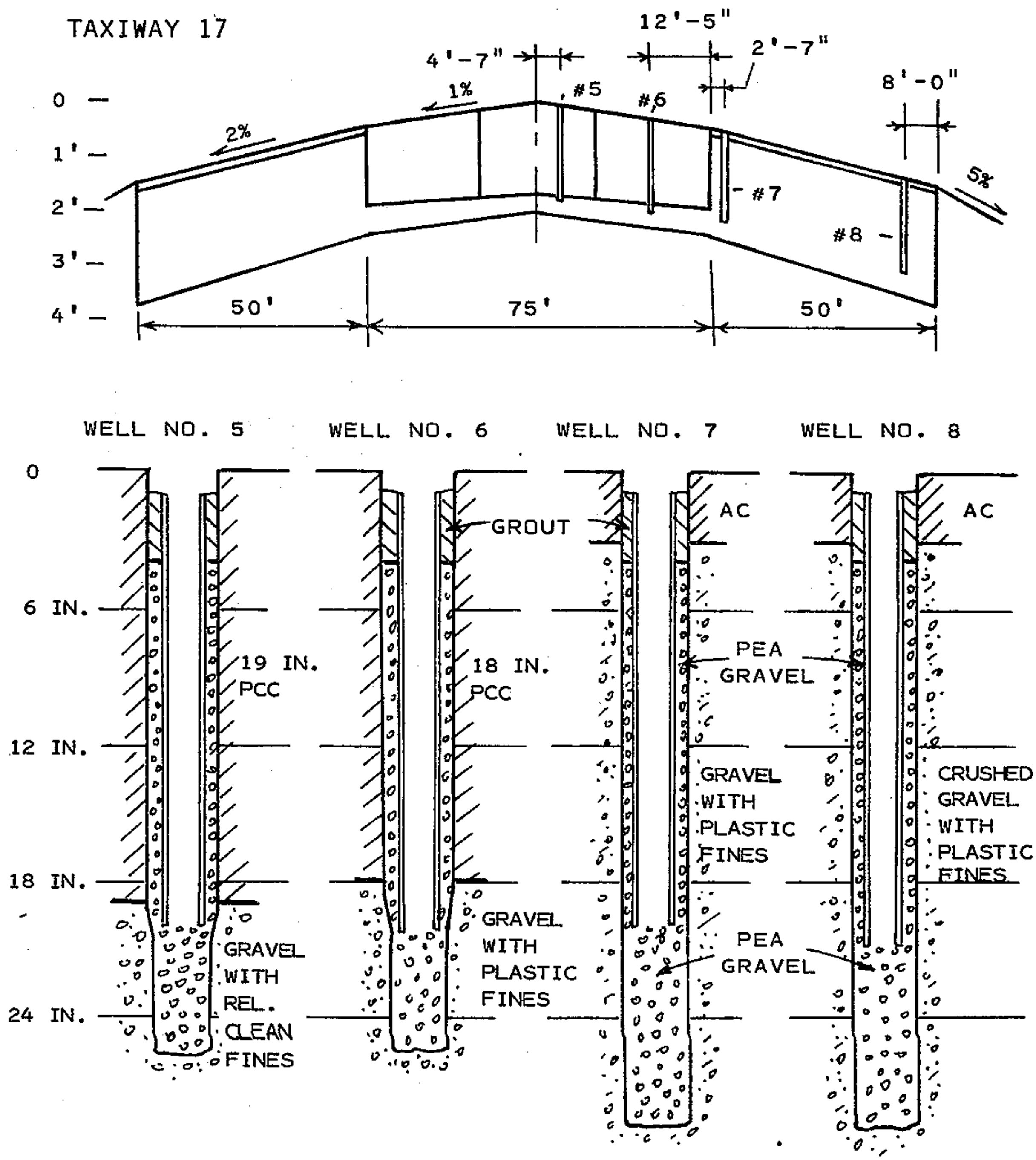

Figure E-3. Logs of wells 5 to 8.

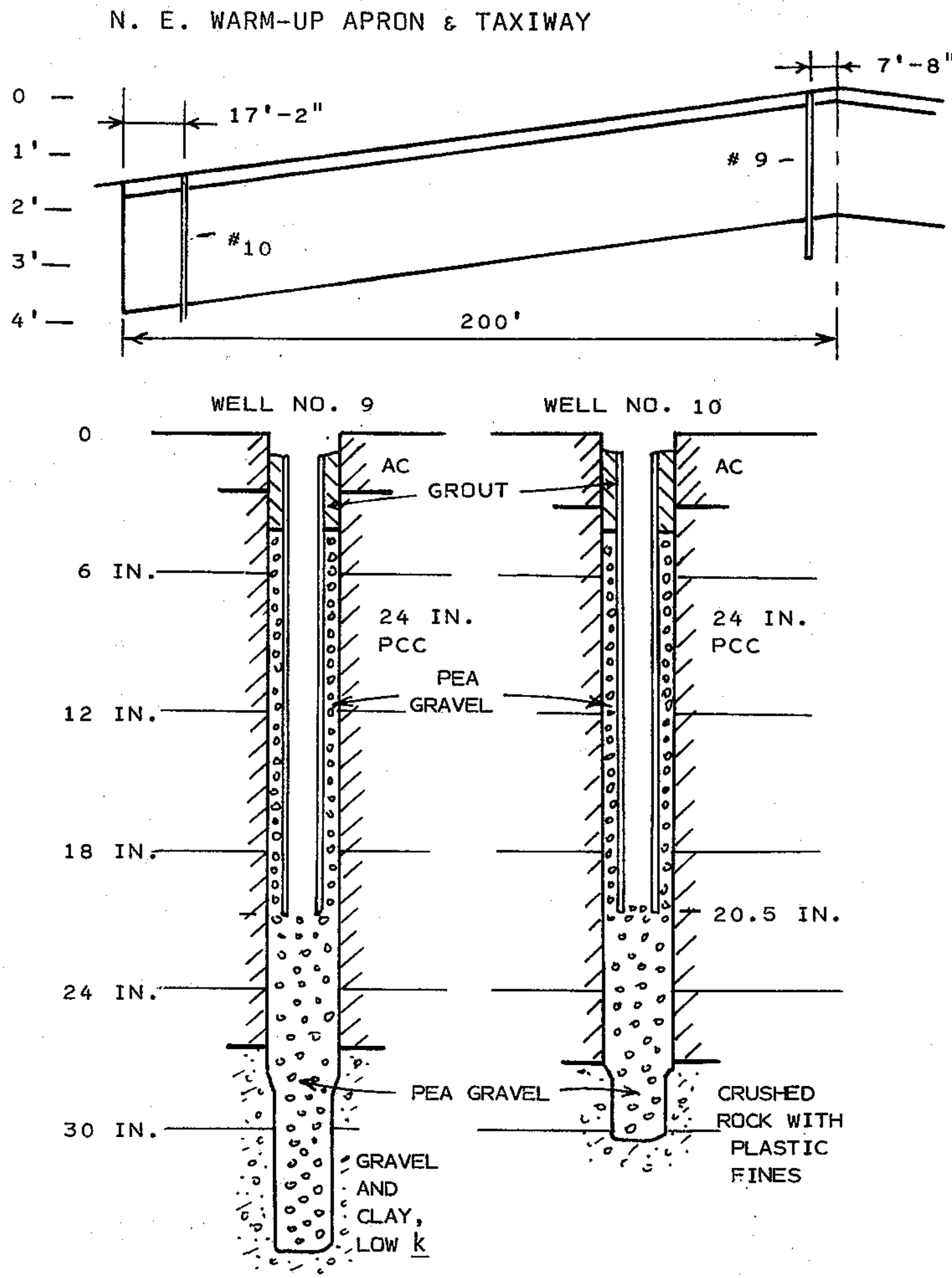

Figure E-4. Logs of wells 9 and 10.

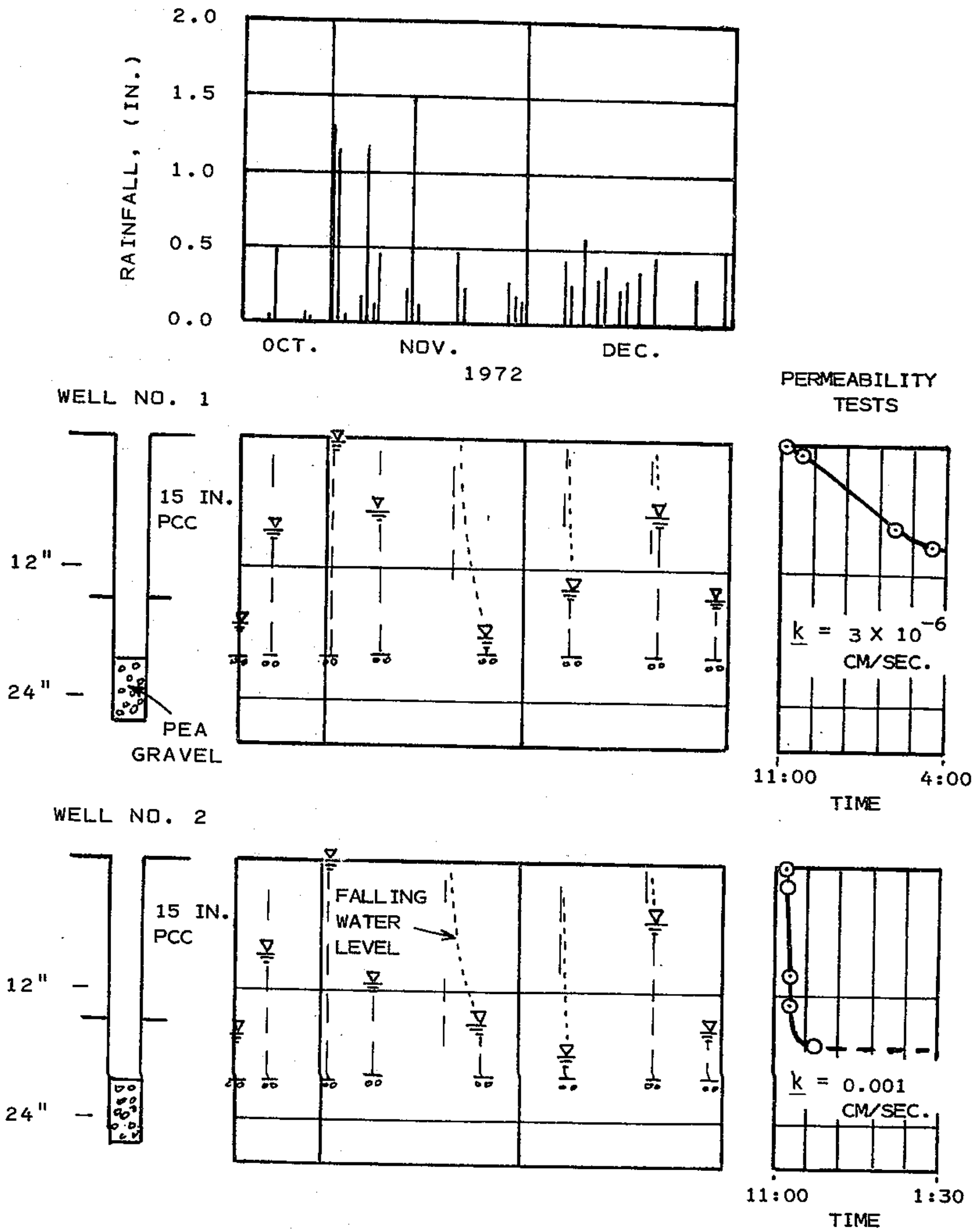

Figure E-5. Field data for wells 1 and 2.

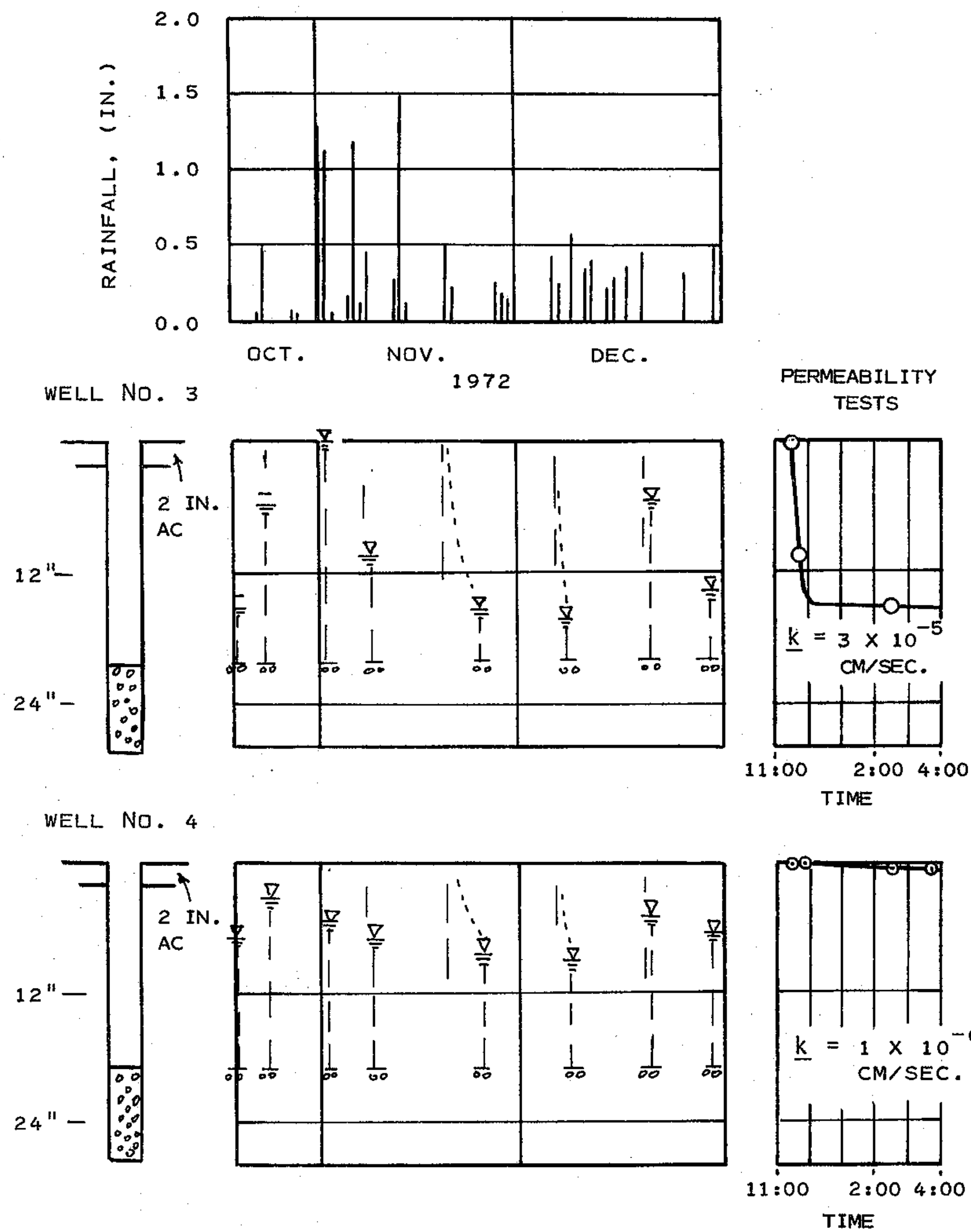

Figure E-6. Field data for wells 3 and 4.

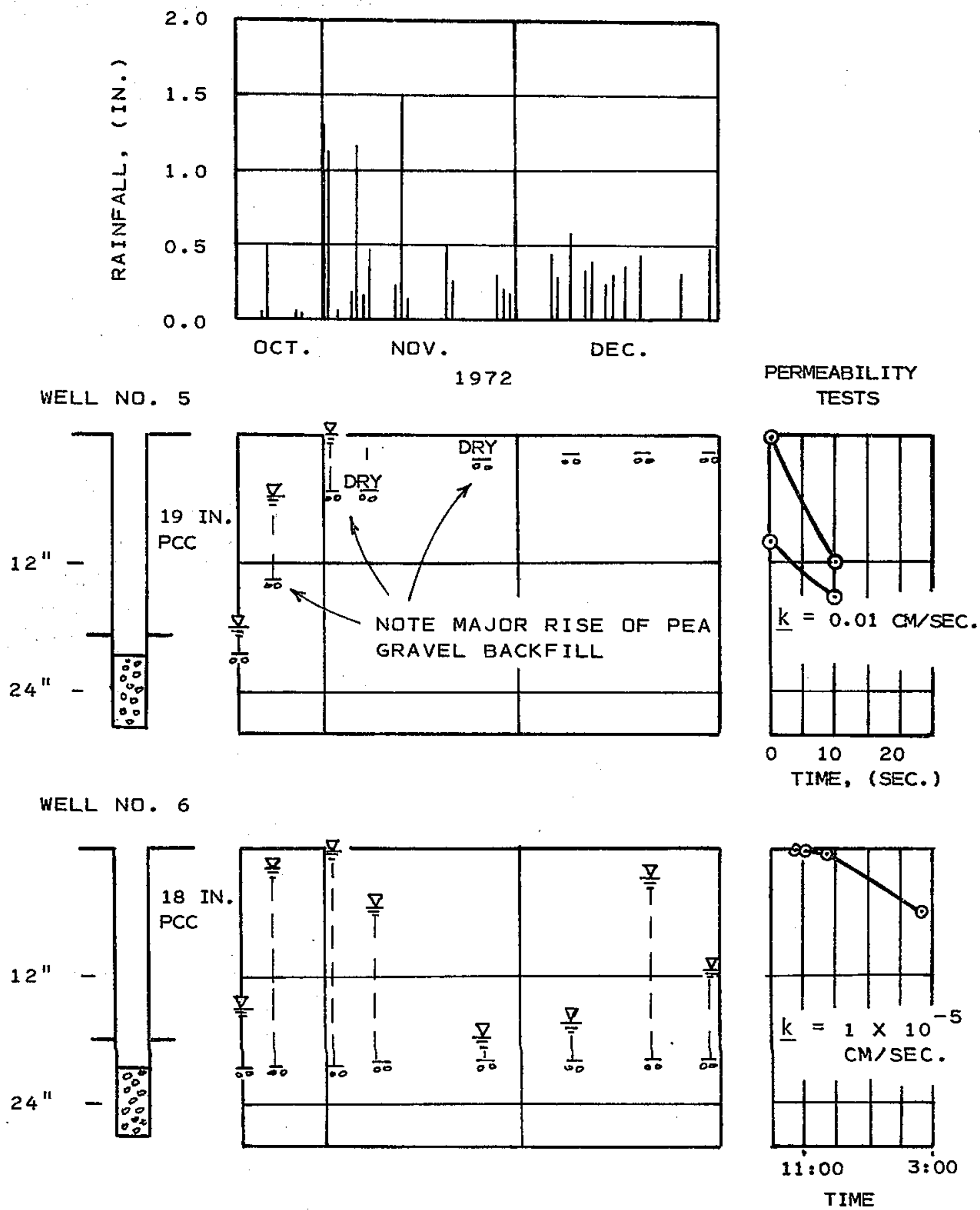

Figure E-7. Field data for wells 5 and 6.

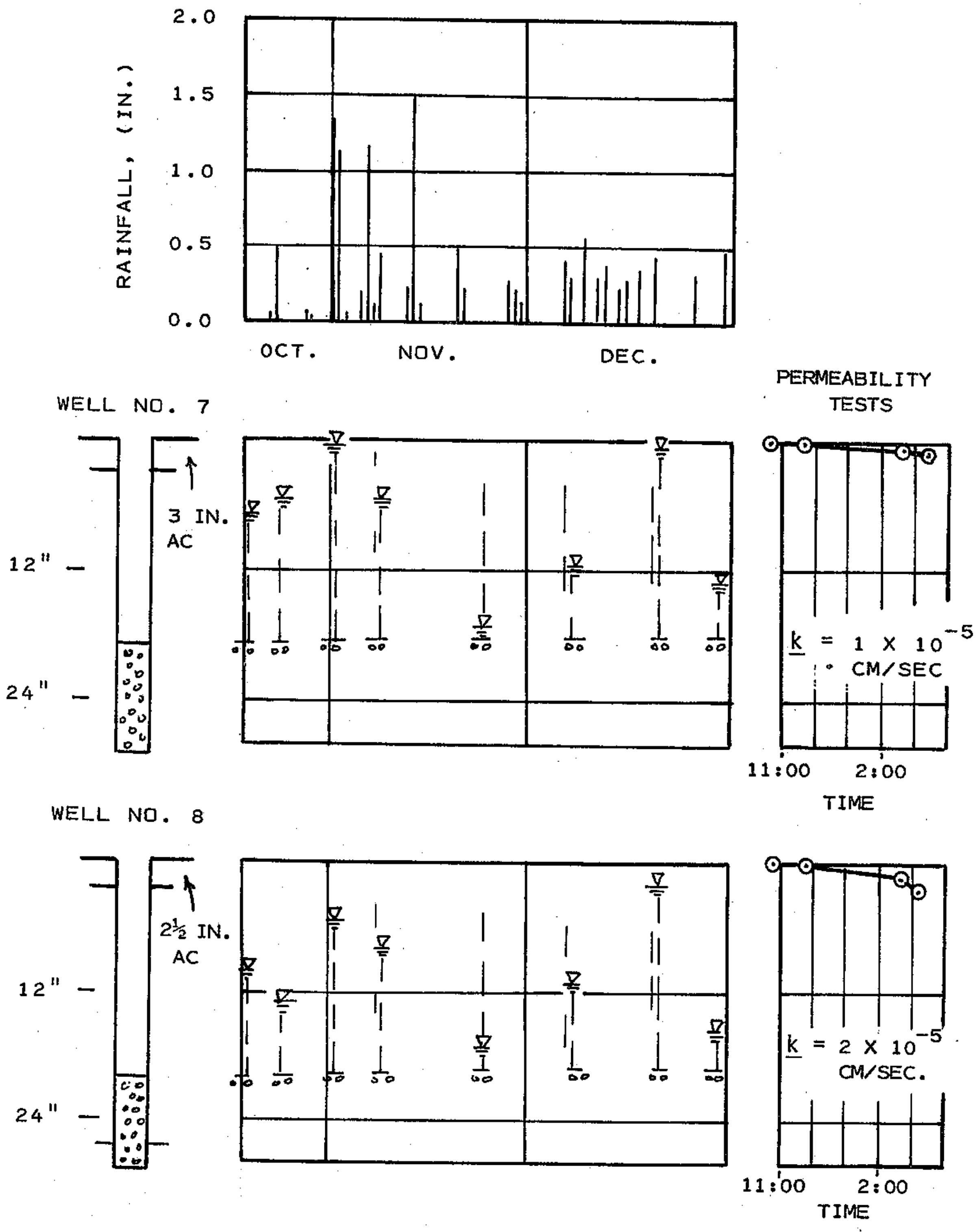

Figure E-8. Field data for wells 7 and 8.

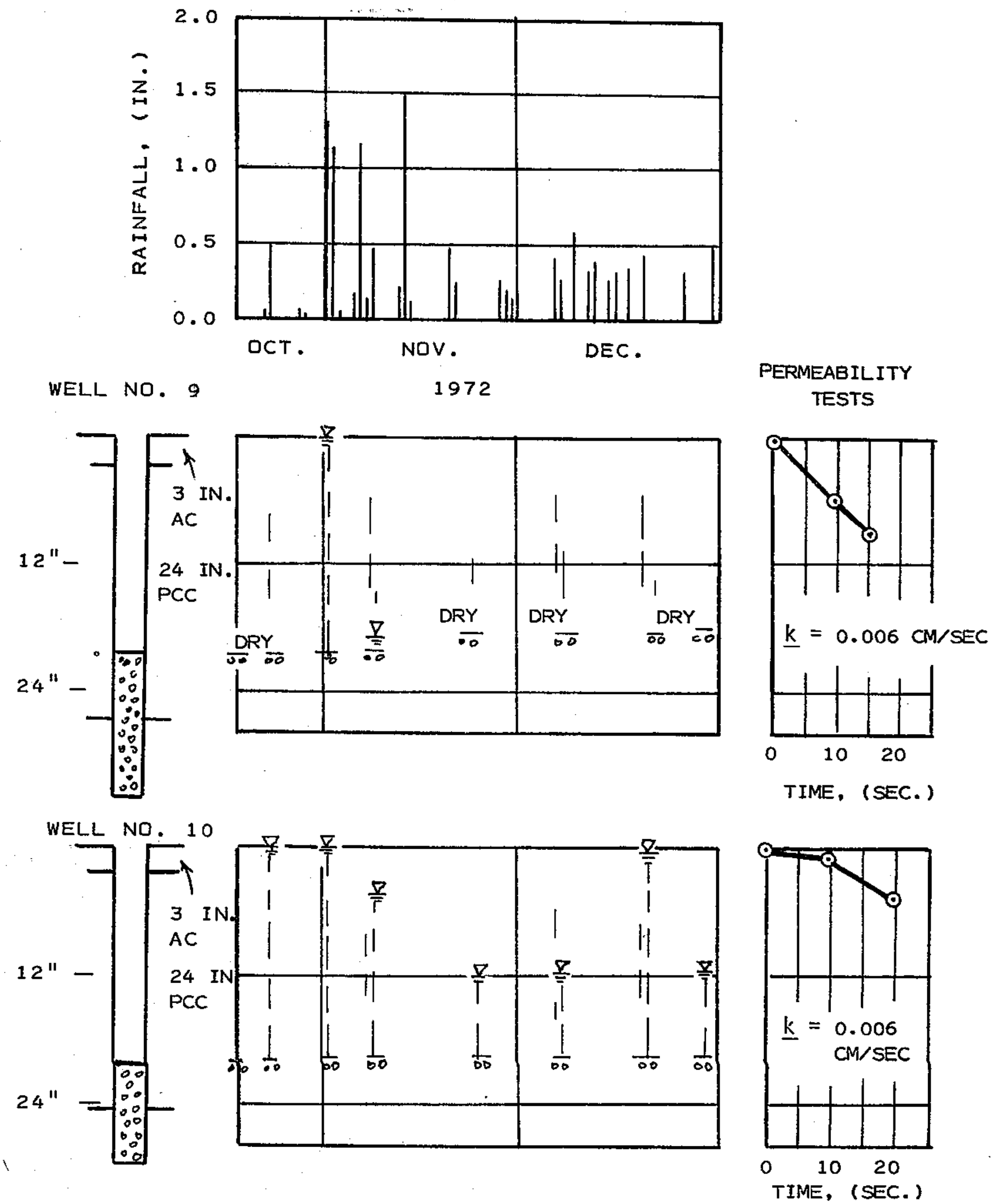

Figure E-9. Field data for wells 9 and 10.

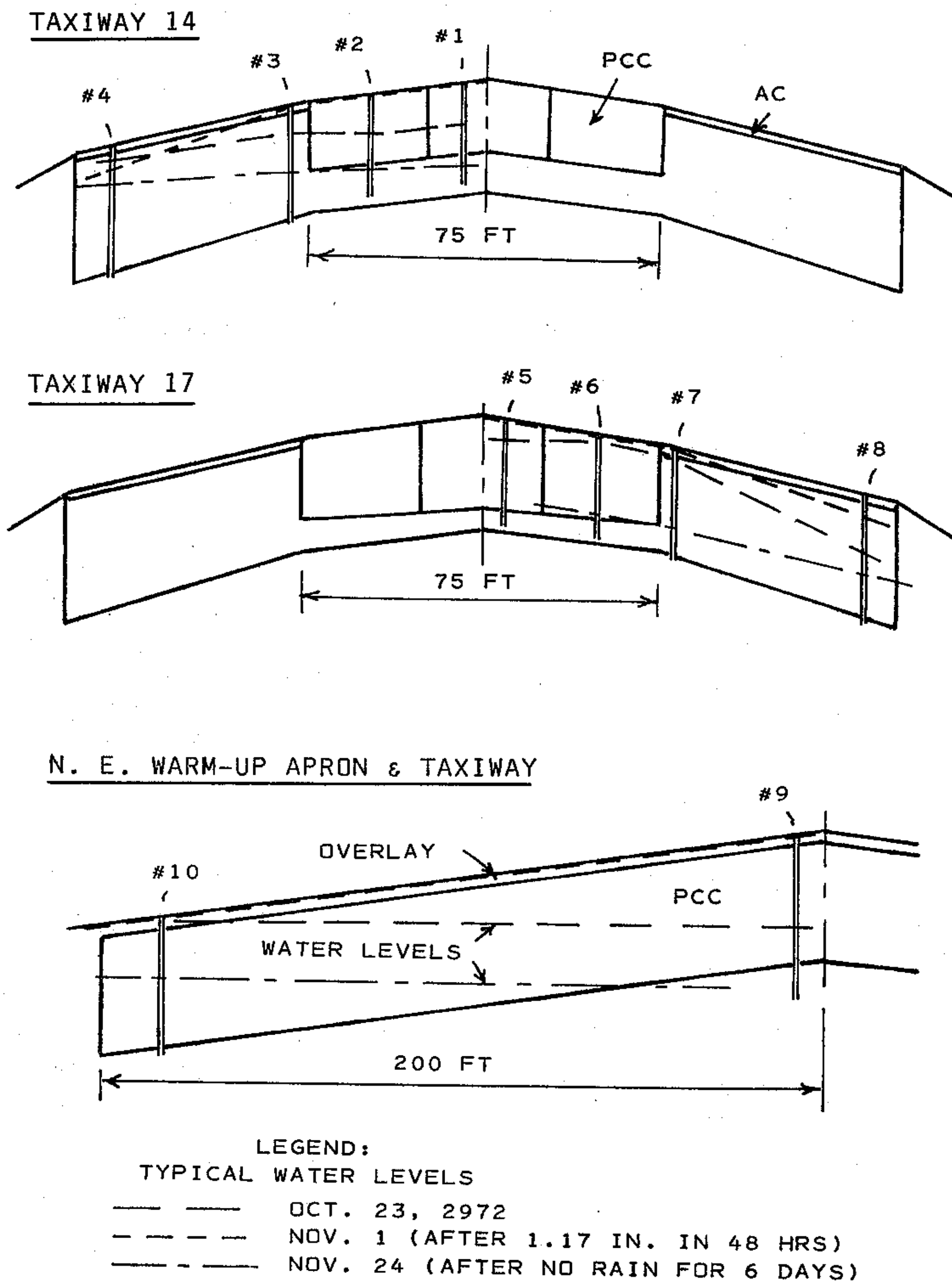

Figure E-10. Typical water profiles.

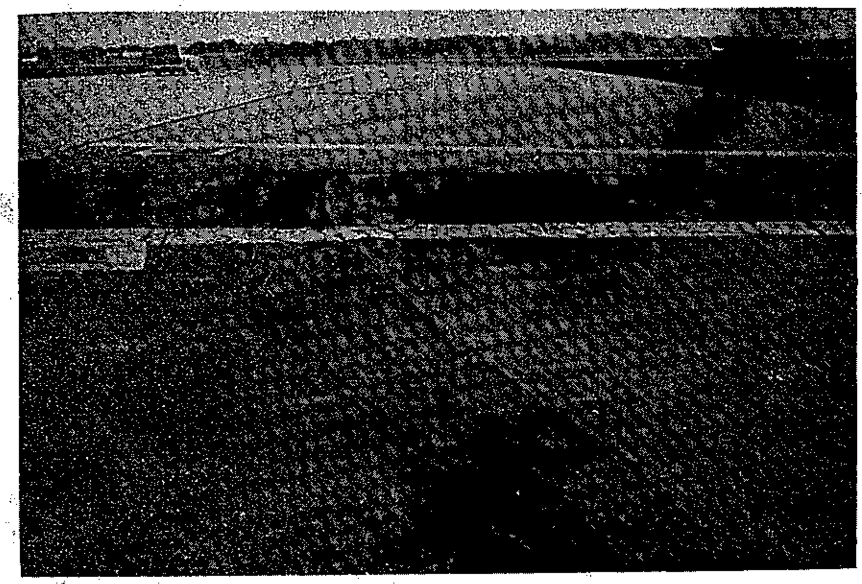

Figure E-11. Looking toward site of Wells 1-4 in Taxiway 14; deteriorated shoulder in foreground, has been damaged from excess water and frost action; the wells were installed later in vicinity of vehicle.

Figure E-12. Photo shows bleeding stains near site of Well 10 (which was installed later near edge of pavement); well develops small artesian pressure after rains.

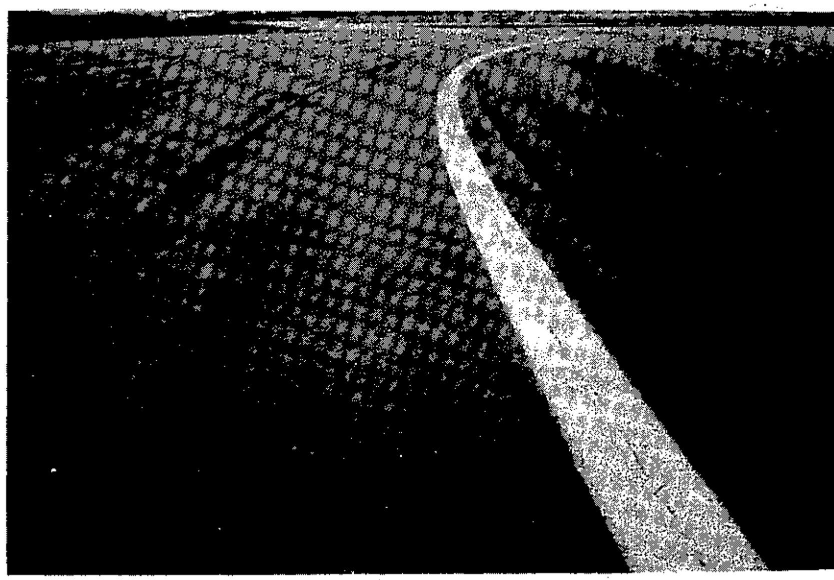

Figure E-13. Photo of NE Warm-up Apron near site of Wells 9 and 10 (installed later); crown area appears to drain rather rapidly, lower edge does not; Well 9 was drilled near the crown, Well 10 near far left edge; photo taken 9-1-72; wells drilled 10-18-72.

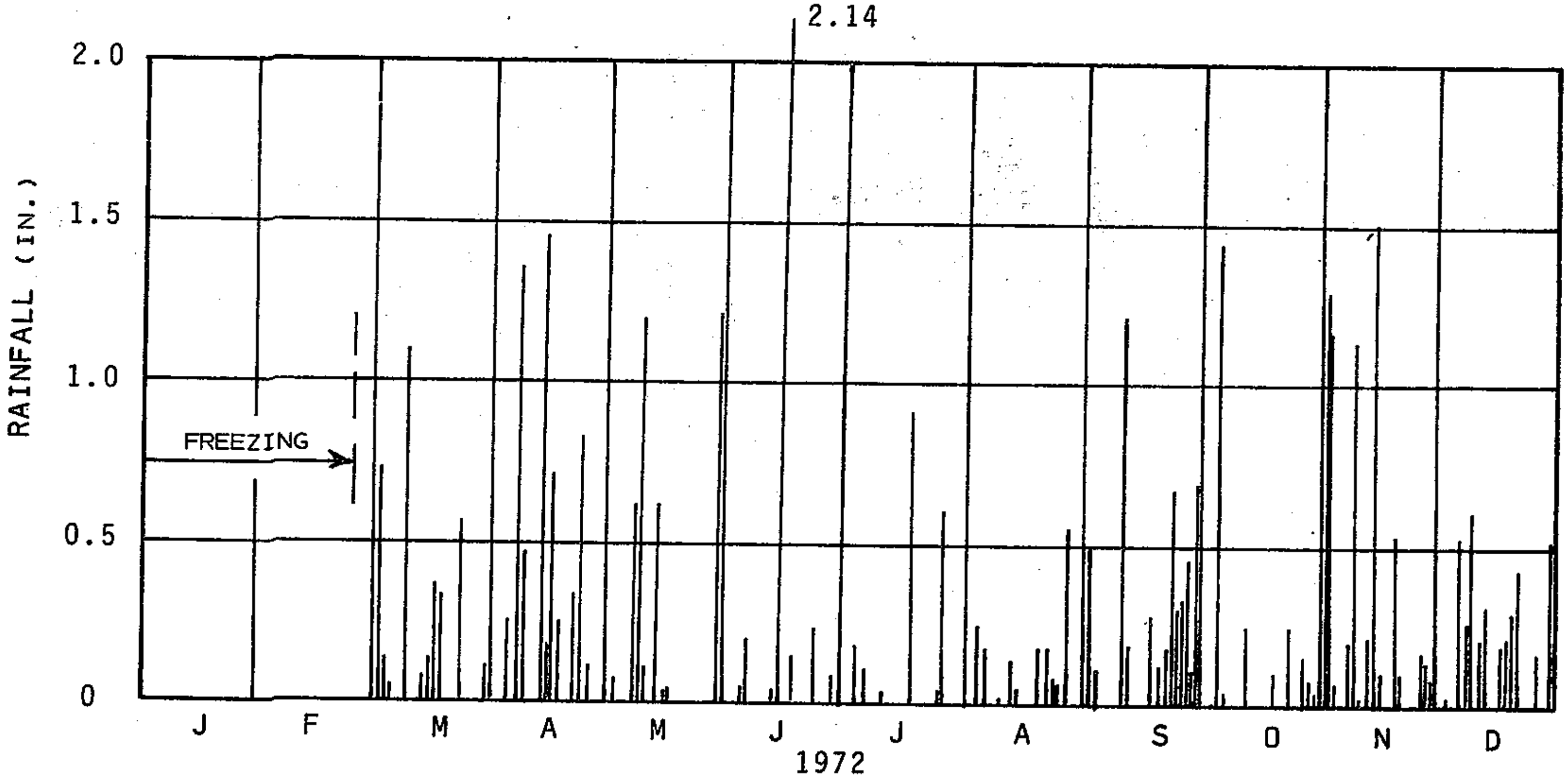

Figure E-14. Rainfall events near Airfield F in 1972.

APPENDIX F

Field Investigations: Airport G

CONTENTS

FIGURES

1 GENERAL INFORMATION

The objective of this study is[1] ". . . to define the various surface and subsurface drainage systems currently used with airfield pavements . . . ," and to evaluate several selected airfields in the U. S., including ". . . airfields rated to have 'good' and 'bad' drainage systems. . . ." Early in the initial phases of the project, it was learned that a commercial airfield had a failed runway that was completely reconstructed in 1969 with a comprehensive subsurface drainage system.

A study conducted by an engineering consulting firm revealed that excess water was the primary cause of the failure of the old runway system (in combination with traffic). Since the native soil underlying the airport is a very impervious micaceous clay, natural drainage is extremely slow. The annual rainfall of about 40 or 50 inches is distributed fairly evenly throughout the year; however during the past year (1972), over 9 inches fell in January, about 12 inches total fell in May, June, and July, and the Fall was relatively dry (see Fig. F-12).

The old pavements of Runway 9L-27R, although constructed on an aggregate base, were very poorly drained. In addition, heavy sod at the edges of the pavements caused surface water to stand for prolonged periods on outer edges of the pavements. Thus, both subsurface and surface drainage conditions were not good.

Early in 1969, under increasing volumes of airplane traffic, the 10,000-ft x 150-ft East-West runway then known as 9L-27R, began rapidly deteriorating with excessive spalling and cracking which was attributed to pumping and loss of support due to general overloading of pavements in a very poorly drained condition. The loss of structural support led to extreme deterioration of the pavements with excessive down time, patchwork, and danger of foreign object damage (FOD) to engines from stones and dislodged pavement debris on the surface.

In some of the lower elevation areas, the accumulated water was forcefully ejected under the weight of the planes to such heights and with such regularity that one spot was nick-named "Old Faithful."

In the development of the new design for the runway and taxiway system, the airport engineers decided to "go back to the principles of McAdam" and include a comprehensive subsurface drainage system in the pavement structure. The pavements as rebuilt in 1969, in the remarkably short time of 40 days consisted of 16-in. thick PCC pavements on a 6-in. thick crushed aggregate subbase over a herringbone drain system containing 16 miles of pipes. The

[1] Part II - Section "F", Solicitation No. DACA 23-72-0012, "Services to Prepare a Report on Methodology and Effectiveness of Drainage Systems for Airfield Pavements," Chicago Dist., Corps of Engineers, Chicago, Illinois.

first operation, after removal of the old deteriorated pavement and grading the subgrade to proper elevations, was to stabilize the top 6 inches of the clay subgrade by mixing and compacting with 10% of cement to give the contractors a "safe, weatherproofing working-platform." Next, trenches were cut into the stabilized working platform to install the 16 miles of 6-in. and 8-in. diameter perforated metal pipe in a herringbone pattern under the pavement areas and longitudinal edge drains and outlet pipes. Coarse stone was used for backfilling under and around the pipes in the eastern part of the runway, and a blend of stone and crusher fines were used in the western part (see Fig. F-1 for a plan of the field and the runway-taxiway system). Over the backfilled and compacted drains a 6-in. thick layer of densely graded crushed stone was placed and compacted with vibratory rollers. After the subbase was completed, the PCC pavement was placed. Transverse joints were cut every 75 ft. with diamond-tipped saws making two cuts: the first 4 inches deep and 1/8 in. wide; the second 1-1/4 in. deep and 1/2 in. wide. A 5/8 in. polyethylene cylindrical foam filler was placed in the joints and sealed with an FAA-approved sealer. In all, about 120,000 feet or 23 miles of joints were prepared in this manner.

The herringbone drains under the pavements feed the water and that enters to longitudinal pipe drains along the lower outside edges of the pavements, and through pipe outlets (spaced every 500 ft) to manholes or to the earth slope south of the runway. Regular inspections, started a short time after the runway was completed, confirmed the effectiveness of this system in removing water from the pavement foundation. An engineer commented to the writer that if all of this water was not being removed, a good deal would be accumulating within the structural section.

Selection of Airport G's Runway-taxiway 9L-27R system as one of the field investigation sites for this study was based on several factors: (1) this is a major airport; (2) natural drainage in the subgrade is extremely poor; (3) rainfall in the area is relatively high, with mild temperatures; (4) severe damages have occurred to other pavements because of excess water and poor drainage; (5) the PCC pavements were provided with a joint-sealing system considered to be one of the best that had been developed; and (6) the new pavements were equipped with a comprehensive underdrain system with pipe outlets at locations where discharge could be observed and measured.

Observations by the airport engineers and the writer of this report indicate that water can enter through apparently "sealed" joints and unsealed cracks in large quantities; and begins to flow out of the underdrain system within the first hour after the start of a rainstorm. The outflows drop off very rapidly during the first 2 or 3 hours after the rainfall diminishes, and trail off to very small flows after 10 to 20 hours (see Fig. F-11).

2 FIELD INVESTIGATIONS

Because of the extremely high traffic volumes being handled, it was not possible to consider the installation of observation wells in any of the pavements constructed in 1969 with the special under-drainage system. The airport director gave his permission for the Runway 9L-27R drainage system to be used in this study, including the physical inspection of the site.

On August 24 and 25, 1972, the writer accompanied by engineers from the airport engineers' office, had made initial site inspections in the general vicinity of Runway 9L-27R, and examination of construction of the new runway-taxiway system that was underway at that time. Figure F-2 shows a backfilling operation for the construction of an underdrain in the new work, which was generally similar to the way underdrains were built in some of the 1969 construction. A sample of the ballast material being placed in the 1972 construction was sent to a Sacramento laboratory for a gradation test. This test indicated the following percentages of sizes for dry weight:

Size or Sieve No.	Percent Passing
1/1/2 in.	100
1/2 in.	52
No. 4	31
No. 16	21
No. 50	13
No. 100	8
No. 200	3.5

The writer has worked with blended aggregates of comparable gradations which had laboratory tested coefficients of permeability in the order of 0.01 cm/sec (30 ft/day), but the ballast under Runway 9L-27R appears to behave like a material with a coefficient of permeability of at least 0.1 cm/sec (300 ft/day). Blended aggregates sometimes segregate during placement, producing zones of coarse material interwoven between zones or stringers of fines, and effective permeabilities may be much higher than for well-mixed blends. In cases like this, the sorting can be beneficial, if it increases flows without causing other problems.

In a series of tests made by the Cold Regions Research Lab. (CRREL), field permeability tests on base and filter materials gave coefficients of permeabilities 10 to 15 times greater than laboratory tests, and the differences were attributed to segregation and lamination of the base course materials during construction.

Figure F-3 shows the expanded end of a neoprene joint seal used in the 1972 construction. Engineers of the airport engineers' office said this seal is approximately equivalent to the seals used in the 1969 construction.

After this airport had been selected as a field investigation site, the writer was able to physically occupy and examine portions of the 1969 construction. This was done on November 13 and 14, 1972, in the company of engineers from airport engineers' office. At that time, detailed inspections were made of typical surface conditions. It was evident, for example, that the joint system had been unable to keep surface water out of the pavements, and the decision of the airport engineers' office to drain the pavements was very wise. Engineers of the airport engineers' office explained that the flow of water was noticed coming out of the subsurface drainage system's discharge pipes, during and after rainfalls, within a few months after completion of these pavements. Figure F-4 shows a typical "sealed" joint that has opened enough to allow large volumes of water to enter. Figure 5 shows an open shrinkage crack that also allows the free inflow of surface water.

During the site inspection on Nov. 13, 1972, a very light rain fell on a portion of the pavements that were being inspected. At that time, it could be seen that water was entering into both joints and cracks in the pavements (see Figures F-4, F-5, and F-6). At a low sag, it was noted that water was standing over the joints in the pavement, suggesting the possibility that some localized spots such as this one might be somewhat slower draining than the system as a whole (see Fig. F-7).

In order to test the degree of openness of typical joints in the 1969 pavements, a gallon jug of water was poured onto the pavement at several locations, and it was seen that the water disappeared rapidly into the joints. Figure F-8, for example, shows a test in which 1 gallon of water entered into about 5 feet of joint in about 1 minute.

A major part of the study of the effectiveness of the drainage system involved the observation and measurement of outflows from underdrain pipes during and after several significant rainfalls late in 1972. During the visit in November 1972, it rained heavily during one night, and about 12 hours later one of the outlets was still flowing about 2 gpm (see Fig. F-9). High water marks indicated that this pipe frequently discharges much greater amounts, and at times flows about half full.

3 OBSERVATIONS OF FLOWS FROM THE PAVEMENT DRAINAGE SYSTEM

Since widespread experience is proving that the major amounts of damage to pavements is being caused by wheel impacts on sections containing free water, it would seem that the analysis of the movement of water into and out of structural sections would be a routine practice. Although the principles upon which suchaan analysis can be made were published by H. Darcy in 1856[3] only recently[4,5,6,7] has any attempt been made to carry out such computations. The seepage requirements of drains for pavement structural sections have been treated as qualitative problems, when in reality they are quantitative problems, having specific solutions for specific situations.

Methods for analyzing seepage requirements for subsurface drains (using the Darcy equation or flow nets) were described by Cedergren[4,5], by Lovering and Cedergren[6] and are presented in a new booklet issued by the FHWA, Washington, D. C. in January, 1973[7]. Opportunities for measuring the inflows into pavements and the outflows through subsurface drains are very limited, as very few pavements have been provided with drains where these measurements can be made. Runway 9L-27R is ideal for this type of observation.

In the case of concrete pavements such as those of Runway 9L-27R and its taxiways, even the modern joint sealing system that was used here could not be counted on for a high level of watertightness for very long. Within a few months after completion of these pavement, the engineers noticed a flow of water coming out of the underdrain pipes. Figure F-1, previously noted, is a small-scale plan showing Airport G as of March, 1971. It shows the locations of the 1969 reconstruction (9L-27R Runway) in relation to other runways and the 1972 construction.

Figure F-10 gives a small-scale plan and profile of Runway 9L-27R, and a tabulation of outflows that were observed on May 4, 1970 during a routine check of the drainage system. These readings were made a number of hours after a rain, when flows were low. They are presented to give an indication of the distribution of the various outlet pipes that were observed to be discharging water. It is seen that essentially all of the observed outflows were located at the lower portion of the runway. Since virtually no water was recorded as coming out of the pipes near the ends of the runway drainage system, it seems possible that water from the herringbone drains is entering into and flowing along the edge drains to the lower elevations, where it can be seen emerging from exits.

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3 H. Darcy, *Les fontaines publiques de la ville de Dijon* (1856).

4 H. R. Cedergren, *Seepage, Drainage, and Flow Nets* (John Wiley & Sons, 1967).

5 H. R. Cedergren, "Seepage Requirements of Filters and Pervious Bases," *Proceedings of the Soil Mechanics and Foundations Division, ASCE*, paper 2623 (October, 1960), pp. 15-33.

6 W. R. Lovering and H. R. Cedergren, "Structural Section Drainage," *Proceedings, International Conference on the Structural Design of Asphalt Pavements*, Ann Arbor, Michigan, (Aug. 20-24, 1962), pp. 773-784.

7 *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*, Federal Highway Administration (FHWA) (H. R. Cedergren and Ken O'Brien & Assoc., January, 1973).

The flow of water through pavement-drainage systems of this kind is comparable to the routing of storms through large, complex river basins. Water is entering into the pavements through cracks and joints of various degrees of tightness at various distances from the herringbone drains and the longitudinal edge drains; some water has nearly instant access to the pipes (where cracks or joints cross over the pipes), but some has to travel appreciable distances in the crushed aggregate subbase to reach the backfill above the pipes in which it flows vertically downward to the pipes and then out through the pipe system.

Readings of outflows at exit pipes such as shown in Fig. F-11 for an outlet at Station 147+58, represent the combined hydrographs of many smaller hydrographs throughout the portions of the pavement-drainage system that are contributing to the flow at that outlet. Localized pore pressure mounds no doubt are building up and falling very rapidly; others may be taking slower trends, requiring about a day or two to dissipate after the stop of a rainstorm. On the whole, it appears that the majority of these pavements drain within a matter of hours after it stops raining. The possibility that some localized areas are accepting and discharging surface water at a somewhat slower rate seems to be indicated by the conditions shown in Fig. F-7, as already noted. The fastest drainage would occur in areas where pipes are directly under or near cracks and joints, the slowest would be in areas where the water has to travel the greatest horizontal distances to reach the pipes. While all of this is going on, minute quantities are slowly seeping downward into the silty clay subgrade, although the quantities drained by the subgrade are believed to be almost negligible in relation to total inflows and outflows.

4 EVALUATING THE EFFECTIVENESS OF RUNWAY 9L-27R DRAINAGE SYSTEM

The ultimate effectiveness of any pavement-drainage system should be measured in dollars worth of performance returned per dollar spent over the life span of the protected pavements. Indications of the probable effectiveness can often be obtained while pavements are still relatively new, since poorly drained and overloaded pavements often begin to show signs of damage from the effects of excess water within a few years. Runway 9L-27R gives every indication of good performance. After four years of heavy commercial traffic it was very smooth, and appeared to be in excellent condition. The pavements that had to be replaced were thinner, were constructed on a 6-in. thick granular subbase, and the micaceous red clay subgrade had not been cement-treated as in the 1969 construction. These differences in design would need to be considered when making a full comparison of the new pavements with the old.

Another way to rate the effectiveness of subsurface drainage systems is in their ability to remove free water from structural sections quickly and effectively. The most serious damages to pavements occur during the periods when they contain free water, so these damages are reduced by reducing the amount of time free water is allowed to remain in structural sections.

The use of simple pipe observation wells to directly measure the rise and spread and fall of saturation mounds is a direct way to verify exposure of pavements to excess water. Measuring outflows from drainage pipes as was done here, gives a broad picture of the overall inflow and outflow characteristics, without the measurement of knowledge of the behavior of local mounds.

Periodic readings of outflows for the discharge pipe near Sta. 147, as shown in Fig. F-11 for a major storm, indicates that the flows drop off quite rapidly within 2 or 3 hours after a storm. From the readings that are given in Fig. F-11, and others that were made for longer periods after rains, it appears that this drainage system is removing most of the water that enters these pavements in about 1/50th of the time required for other pavements that do not have this kind of pavement-drainage system (on comparable subgrades).

According to U. S. Weather Department records, this airport can expect to have 50 to 60 significant showers or rainstorms each year, as may be noted by examining Fig. F-12, which gives the rainfall events near the airport in 1972. Without rapid drainage, pavements in this kind of climate may contain free water essentially 100% of the time each year. Runway 9L-27R and taxiway pavements with their subsurface drainage system may be exposed to excess water during periods of heavy rainfall, and for short periods of time after each significant rainfall event. The total annual exposure of the structural sections of these pavements to excess water is considered unlikely to exceed about 40 days total time each year for the majority of the pavements, with localized areas exposed somewhat greater amounts of time which at present can only be surmised from outflow readings.

On the basis of the information gathered in this study it appears that the underdrain system under Runway 9L-27R taxiway system is reducing the annual exposure of the majority of these pavements to excess water by nearly 90%, which is a major improvement.

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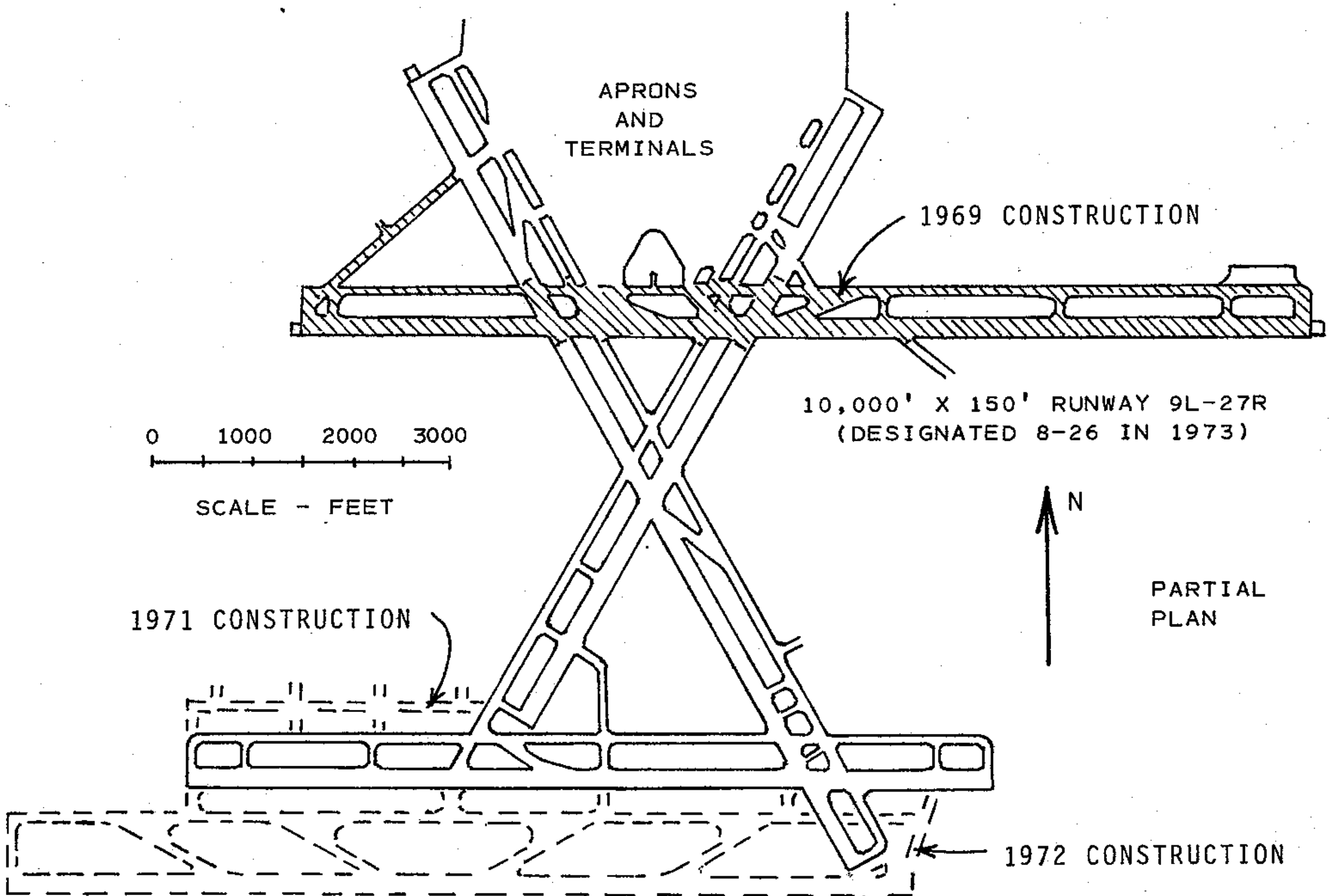

Figure F-1. Airport G layout, March, 1971

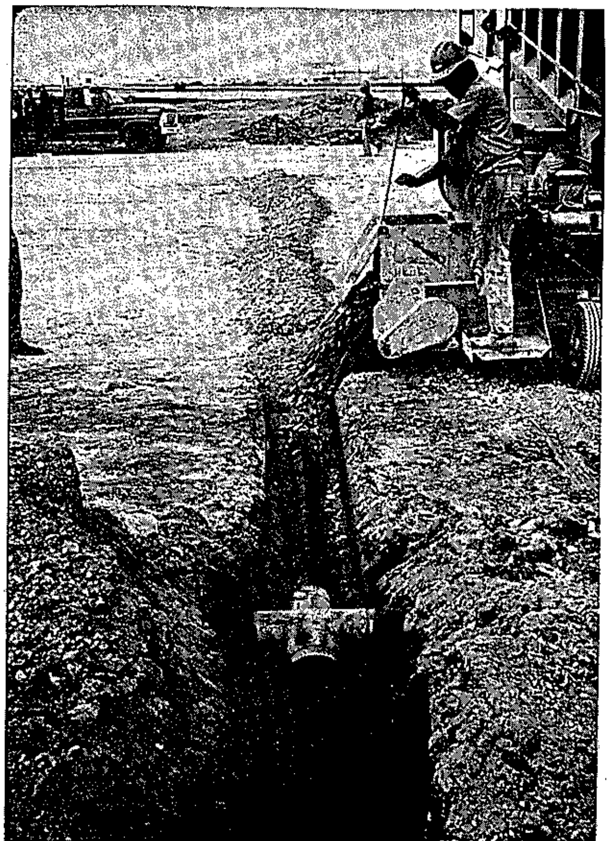

Figure F-2. Placing blend of ballast rock and fines around and over pipe in an underdrain (1972 construction); is similar to material used in part of 1969 work.

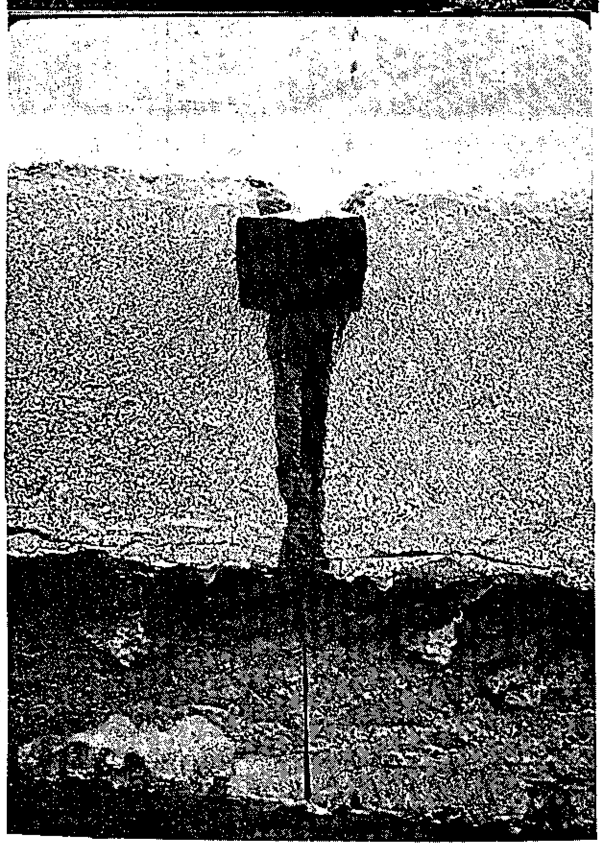

Figure F-3. Expanded end of neoprene seal squeezed into sawed joint in 16-in. PCC pavement of new South Runway (1972 construction); is approximate equivalent of seals used in 1969 work.

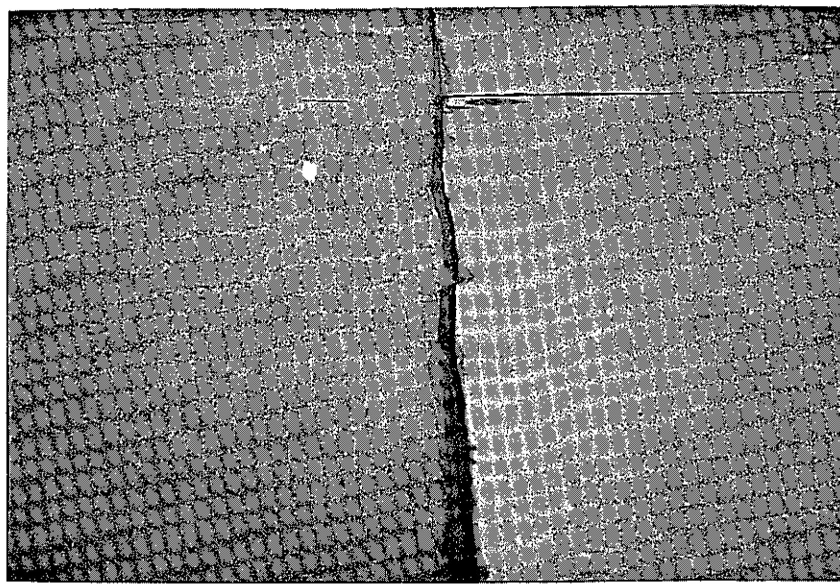

Figure F-4. Opened construction joint in PCC pavement on Taxiway B at Exit G; 1969 construction.

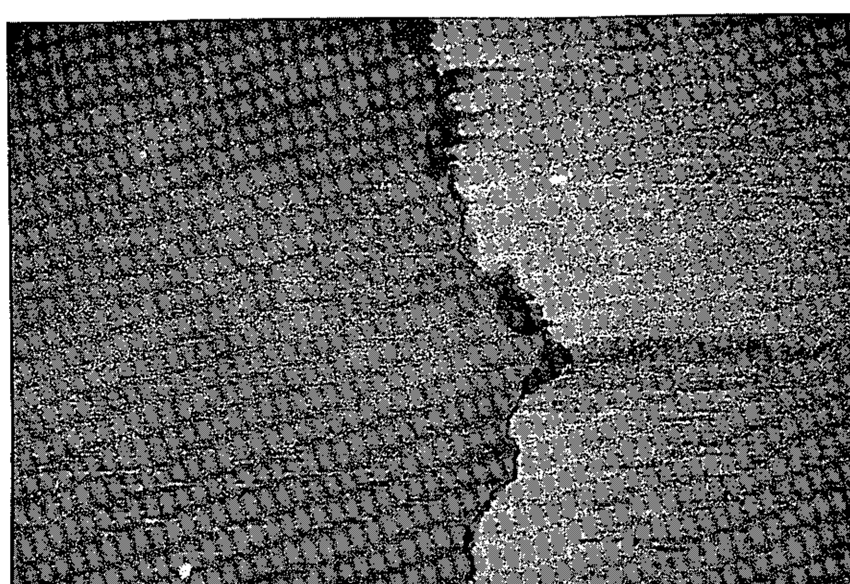

Figure F-5. Open shrinkage crack in Taxiway B at Exit G; 1969 construction.

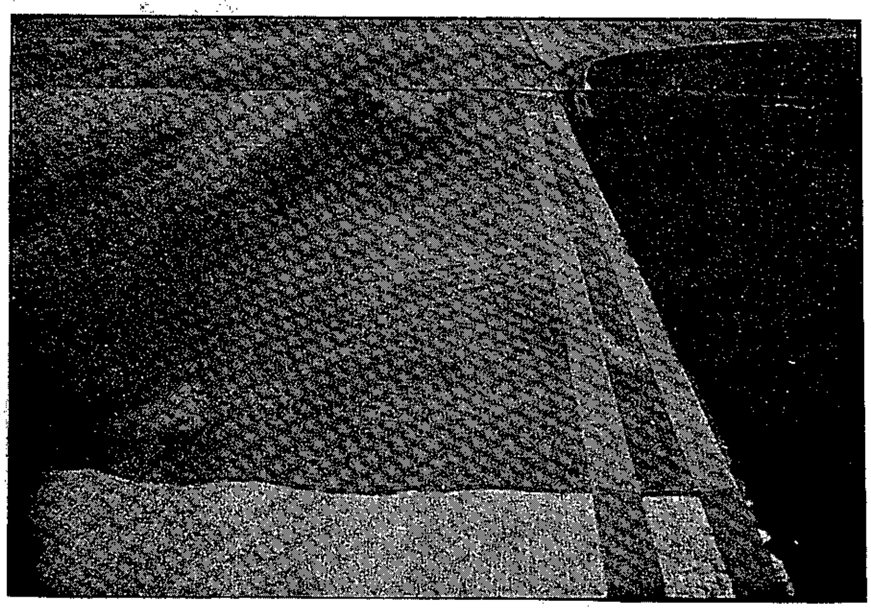

Figure F-6. Shows water entering into cracks and joints in 1969 construction; Taxiway B at Holding Apron.

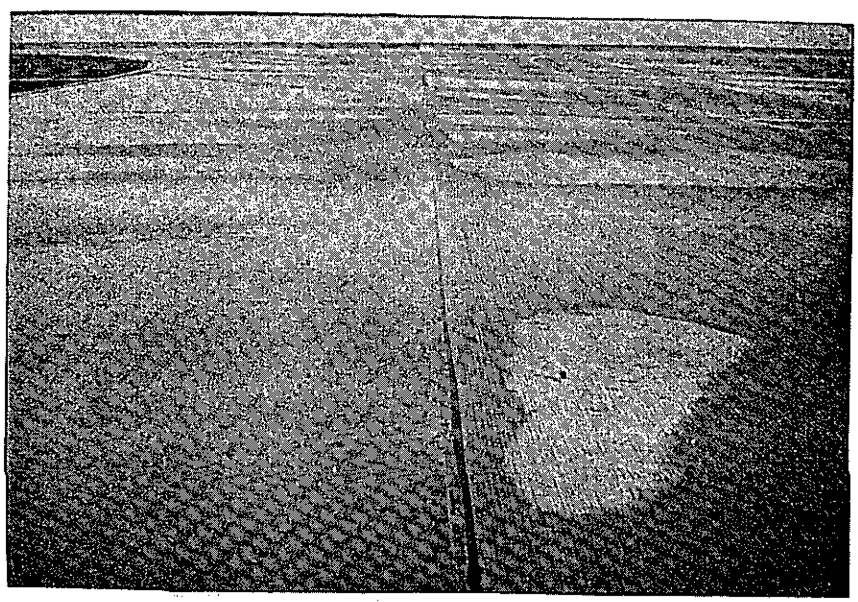

Figure F-7. Shows water standing over a sag in 1969 taxiway; Taxiway B Exit at Holding Apron; may indicate slower drainage than at most areas.

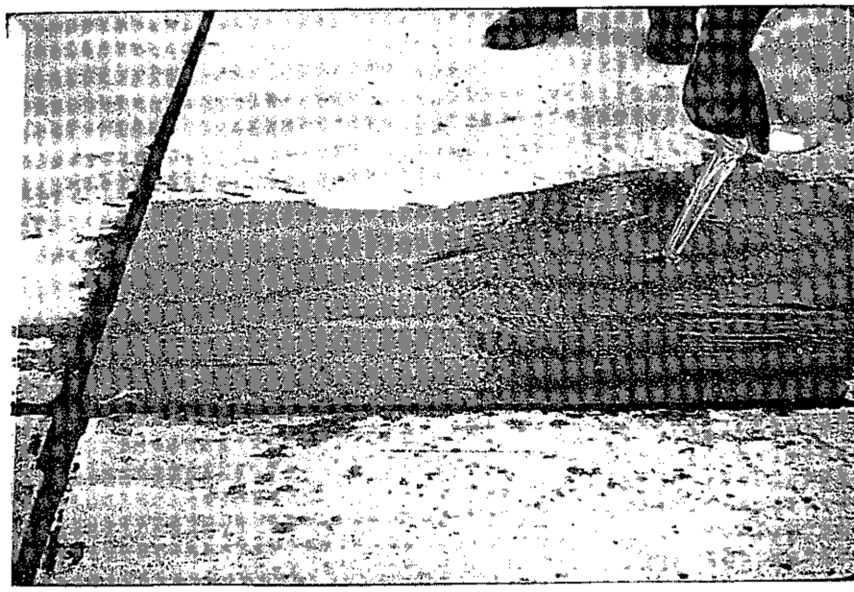

Figure F-8. Shows water entering open joint in 16-in. PCC pavement constructed in 1969; gallon jug of water disappeared into joints shown in photo in about 1 minute.

Figure F-9. Shows outlet pipe flowing about 2 gpm about 12 hours after a rain; on earth slope at Sta. 147+58; note high water marks above half-height of pipe.

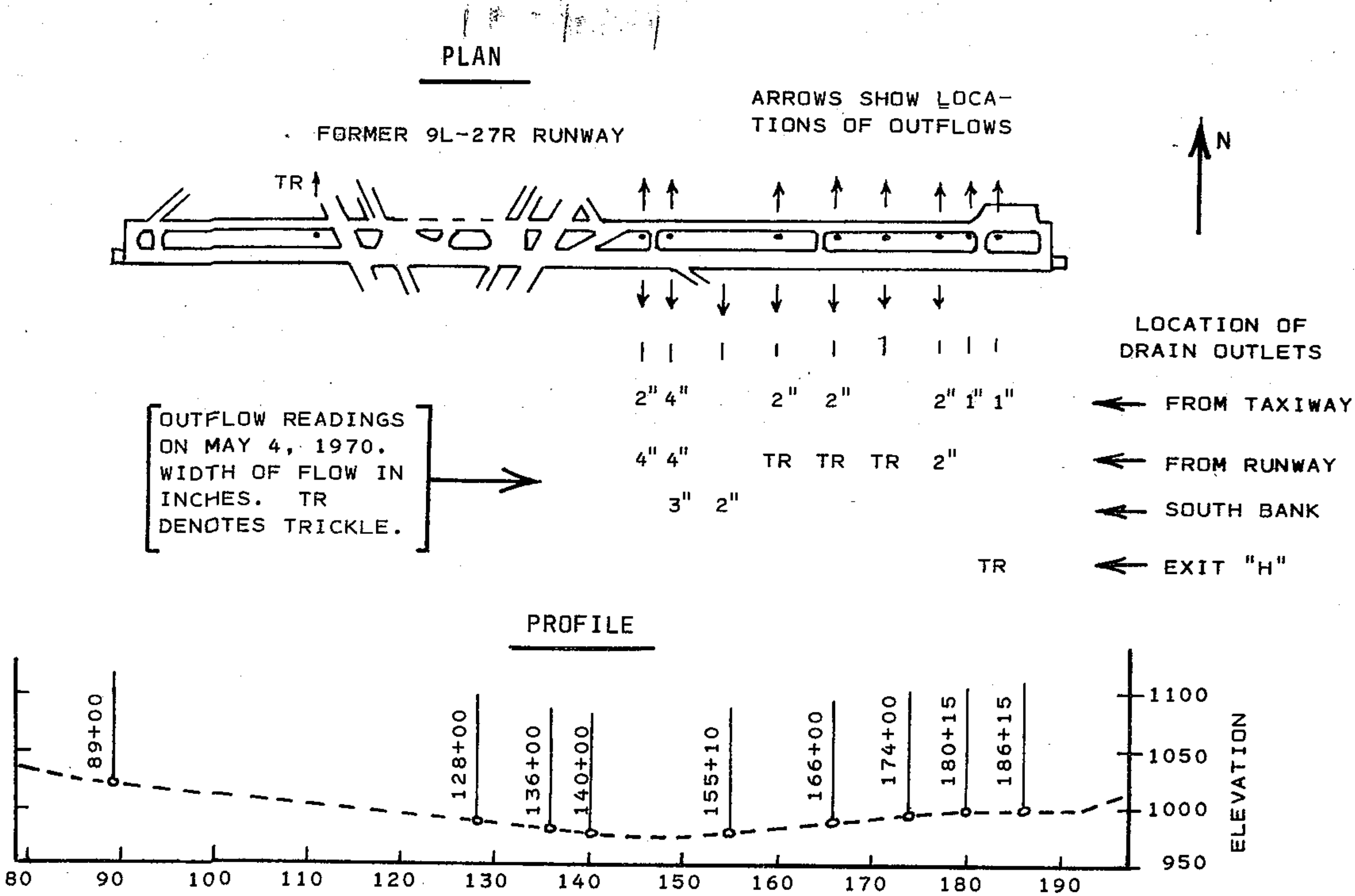

Figure F-10. Drain outflow measurements in May, 1970. Airport G Runway 9L-27R.

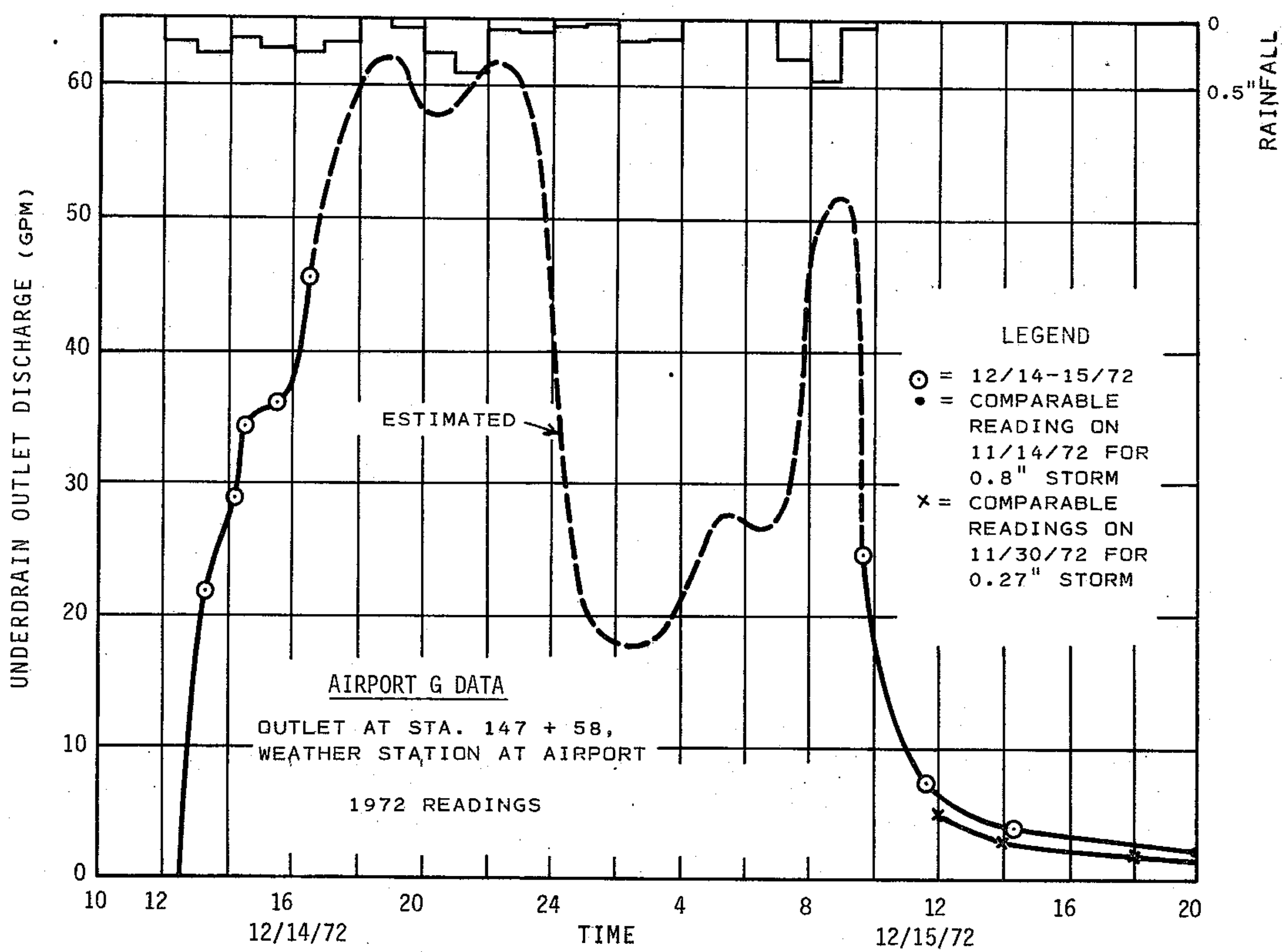

Figure F-11. Outflow hydrograph at a drain pipe.

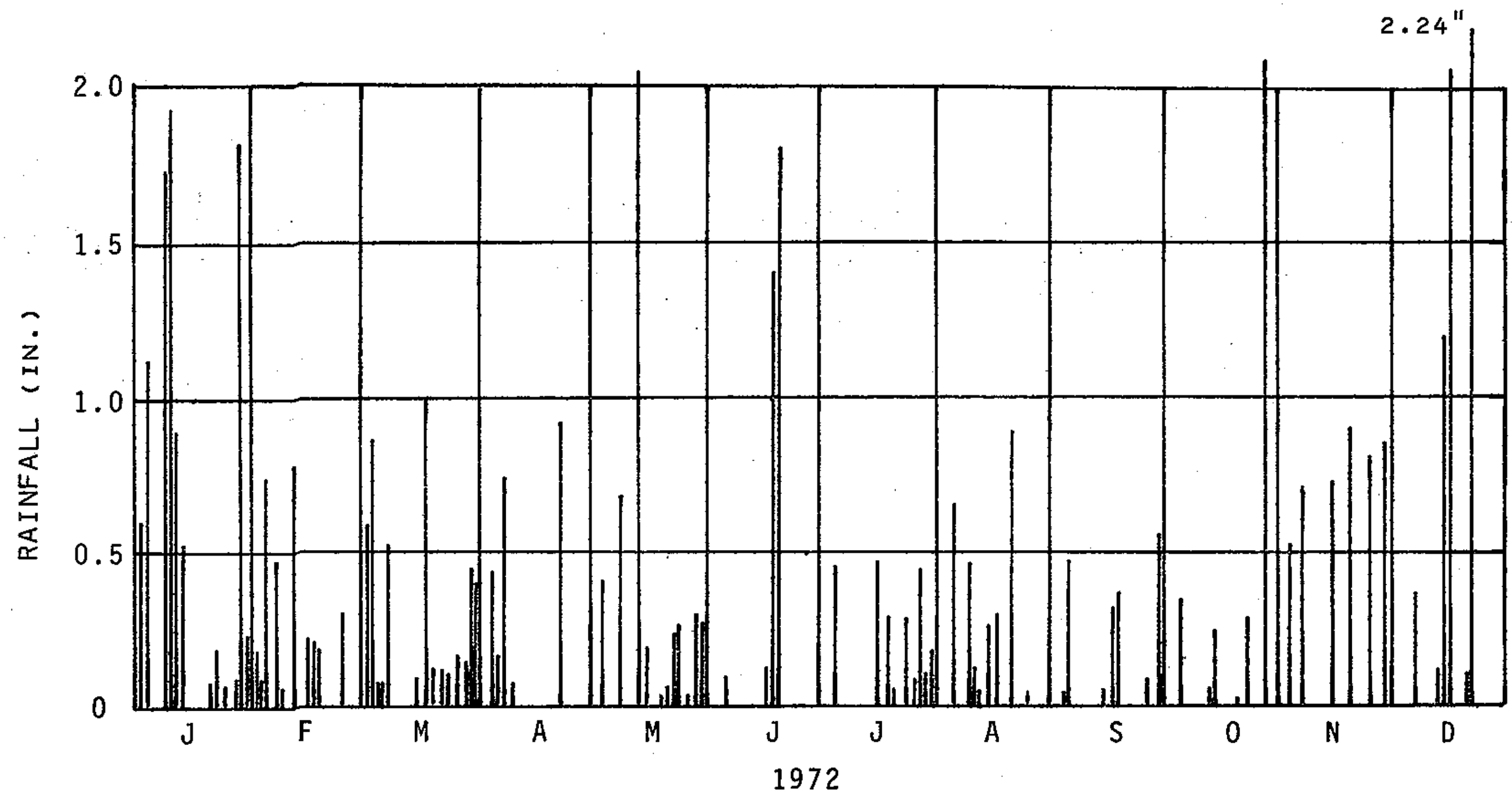

Figure F-12. Rainfall events near Airport G in 1972.

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